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Sludge Incineration and Percipitant Recovery

Volume IV

Research Report No. 107

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SLUDGE INCINERATION AND PRECIPITANT RECOVERY

VOLUME IV

Pilot Scale Multiple-Hearth Furnace Investigations

by

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RESEARCH PROGRAM FOR THE ABATEMENT
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ABSTRACT

This study describes investigations conducted at the Hamilton Water Pollution Control Plant on a pilot-scale multiple-hearth sludge incinerator. The objectives were:

1) to determine in a controlled fashion the fate of a selected number of elements with the normal ranges of operating parameters of a multiple-hearth incinerator handling municipal sewage sludge;
2) to determine the optimal and/or boundary conditions of temperature, throughput capacity (loading rate) and centre shaft speed, with regard to the prevention of clinker formation, while at the same time minimizing the residual organic content of the incinerator ash.

The experimental program consisted of a factorial design which included four levels of temperature, three levels of throughput rate, and three levels of centre shaft speed. Samples of feed, ash and scrubber water were collected at three evenly-spaced intervals throughout the steady-state operating period.

Under the constraints of the experiment, phosphorus, zinc, iron, magnesium, aluminum, nickel, copper, calcium, chromium, lead and silica proved to be conservative and remained in the ash, whereas varying proportions of cadmium, mercury and arsenic were classified into the gas stream. The destruction of total carbon was essentially complete, with the minimum level achieved being 98.7%. The most important factor in determining auxiliary fuel consumption is the water content of the feed sludge. Clinker formation was observed only under conditions of high temperature combined with long residence time within the furnace.

RÉSUMÉ

A l'usine d'épuration de Hamilton, on a poursuivi une étude sur le fonctionnement d'un incinérateur pilote de boues à soles multiples

Les recherches avaient pour buts:

1) d'étudier le devenir, dans un incinérateur de boues à soles multiples traitant des eaux d'égout municipales, d'un certain nombre d'éléments, dans des conditions déterminées et normales de fonctionnement;
2) de déterminer les conditions optimales et limites de la température, le volume de boues incinérées (le rythme de chargement) et la vitesse de rotation de l'arbre central qui peuvent empêcher la formation de scories et réduire en même temps la teneur en matières organiques résiduelles des cendres de l'incinérateur.

Le plant d'expériences comprenait l'essai de quatre températures, de trois volumes de chargement et de trois vitesses de rotation. Par trois fois, à intervalles réguliers au cours de la période de fonctionnement à l'équilibre, nous avons prélevé des échantillons de boues, de cendres et d'eau de lavage des gaz d'émission.

Au cours de l'expérience, le phosphore, le zinc, le fer, le magnésium, l'aluminum, le nickel, le cuivre, le calcium, le chrome, le plomb et la silice se sont révélés non volatiles (ils sont restés dans les cendres), tandis que le cadmium, le mercure et l'arsenic se sont montrés volatiles (on les a retrouvés dans les gaz d'émission). Le carbone total a été presque complètement détruit, soit au plus à 98.7%. Le principal facteur de brûlage du combustible secondaire est la teneur en eau des boues. On a observé la formation de scories seulement sous des températures élevées et après des séjours prolongés dans l'incinérateur.

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CONCLUSIONS

1. Elements that proved to be conservative included phosphorus, zinc, iron, magnesium, aluminum, nickel, copper, calcium, chromium, lead, and silica. Under the constraints of the experiment, these elements remained in the ash and did not exhibit disproportionation or classification due to volatilization.
2. The degree of cadmium volatilization (i.e., its conversion to gas) proved to be a function of temperature. The loss of cadmium from the ash ranged from 25% at 760°C to 56% at 928°C.
3. Greater than 99% of the mercury in the feed sludge was classified into the gas stream under all operating conditions. Since analysis of the scrubber water was not possible at the time of testing, the amount discharged to the atmosphere could not be determined.
4. Arsenic was classified into the gas stream, but was not discharged to the atmosphere. A mass balance on the ash plus the scrubber water accounted for 103% of the input arsenic.
5. The destruction of total carbon was essentially complete over the entire range of operating conditions tested. The minimum level of destruction achieved was 98.7%.
6. The consumption of auxiliary fuel was not affected by burning zone temperature. The temperature effects were also independent of the feed rate and centre shaft speed. The effect of feed rate and centre shaft speed on fuel consumption could not be evaluated because of an underlying bias introduced by the moisture content of the sludge. The fuel consumption was dependent on the total solids content of the feed sludge. Theoretically, autogenous conditions are approached at a total solids concentration in excess of 31%.
7. The sludge from the Hamilton Water Pollution Control Plant could be incinerated in the pilot scale unit without clinker formation at temperatures up to 928°C, provided the residence time within the furnace was kept to a minimum. The only experimental runs in which clinker formation was encountered were at the highest temperature and long residence times (low feed rate and centre shaft speed).

RECOMMENDATIONS

Based on the data generated by the pilot-scale incinerator, the following recommendations can be made regarding the operation of a multiple-hearth incinerator using sludge from the Hamilton Water Pollution Control Plant:

1. The possibility of clinker formation at high temperatures (up to 925°C) can be reduced by minimizing the residence time within the furnace. This may be accomplished by increasing the feed rate and centre shaft speed.
2. A short residence time is also desirable with regard to heavy metals. Although not proven statistically significant, there appeared to be a trend with certain elements whereby the amount remaining in the ash decreased as the residence time increased.
3. The most effective way of achieving significant cost savings is by reducing the level of auxiliary fuel consumption. This could be accomplished by upgrading the dewatering system to decrease the water content of the feed sludge.

1 INTRODUCTION

1.1 Background

Historically, the major effort in upgrading existing municipal wastewater treatment installations has been directed toward effluent quality improvement through process development and refinement strategies. In recent years the handling, treatment and disposal of the sludge generated by conventional municipal wastewater treatment facilities have evolved into an issue of considerable importance. More stringent pollution control regulations and more efficient treatment processes are generating greater quantities of municipal sludge which in turn necessitate more effective sludge management practices. Furthermore, the increasing use of chemical treatment methods, inadequate knowledge regarding potential long-term effects of currently accepted sludge disposal practices, escalating energy and transportation costs, and greater restrictions on suitable disposal sites have been instrumental in focusing attention on the role of incineration in sludge management.

The proposed implementation of a province-wide phosphorus removal program at municipal water pollution control plants in Ontario during the early 1970's was controversial and raised many questions. These indicated a need for a thorough review and reassessment of conventional sludge management practices. One of the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality (COA) called for the establishment of a Research Program for the Abatement of Municipal Pollution.

In 1972, with funding provided by the COA research program, the Wastewater Technology Centre (WTC) initiated a four-year applied research and development program to deal with various aspects of incineration of chemical phosphorus removal sludges. This included an assessment of the technical and economic feasibility of precipitant recovery from sludge incinerator ash. The results of previous work, comprising a comprehensive literature review and laboratory-scale investigations into sludge incineration and phosphorus removal precipitant recovery, conducted as part of this four-year R&D program have already been published in this research report series (Plummer, 1976; Fowlie and Stepko, 1978; Schroeder and Cohen, 1978).

The WTC pilot-scale multiple-hearth sludge incinerator was moved to its present location at the Hamilton WPCP during the spring of 1976. Previously, this equipment had been operated in a field station established by the WTC adjacent to the wastewater treatment plant at the Canadian Forces Base Borden, located approximately 100 km (60 miles) northwest of Toronto. The field station was established at this location in conjunction with COA-sponsored exploratory phosphorus removal chemical treatability studies (Shannon and Rush, 1973). Subsequent full-scale phosphorus removal demonstration studies were carried out at the CFB Borden treatment plant by WTC personnel (Stepko and Vachon, 1978).

During 1974 and 1975, incineration experiments with the pilot-scale multiple-hearth furnace as well as a 2.0-m (6.5-ft) long and 15-cm (6-in) inside diameter rotary-kiln furnace, were performed at this field station on dewatered sludges obtained from eight pre-selected water pollution control plants in Ontario. At that time, four of the eight plants were practising phosphorus removal through chemical addition. Information pertaining to the sludge sources and sludge types has been summarized in Appendix A.

In general, the incineration tests of the CFB Borden field station showed that the lime and alum phosphorus removal sludges did not pose any special operational problems under normal operating conditions for either multiple-hearth or rotary-kiln furnaces. However, copious clinker formation was evident with the iron-rich sludges from the Hamilton and the London Pottersburg WPCP at furnace combustion zone temperatures approaching 925°C (1700°F). Because of mechanical deficiencies and operational problems, the amount of reliable performance and operating data obtained from the incineration tests conducted at CFB Borden was limited. The work, however, did identify the necessity for a single-source sludge and the need for a feed system to the pilot-plant incinerator that would ensure a constant throughput rate. The relocation of the pilot plant to Hamilton and modifications to the feed system were instrumental in solving these problems.

This report describes the pilot-scale investigations conducted at the Hamilton Water Pollution Control Plant (WPCP) by the Wastewater Technology Centre during the period from July, 1976 to May, 1977 with a six-hearth, natural gas fired sewage sludge incinerator.

1.2 Study Objectives

The objectives of the final phase of the four-year experimental program dealing with sludge incineration and precipitant recovery addressed two areas of concern.

The objectives were two-fold: (1) to determine, under controlled conditions, the fate of a selected number of elements within the normal ranges of operating parameters of a multiple-hearth incinerator handling municipal sewage sludge, and (2) to determine the optimal and/or boundary conditions of temperature, throughput capacity (loading rate) and centre shaft speed, with regard to the prevention of clinker formation, while at the same time minimizing the residual organic content of the incinerator ash.

The second objective was related to the present mode of operation of the incinerators at the Hamilton WPCP. Previous full-scale operating experience at the Hamilton WPCP had indicated that operation in the range of 760°C to 875°C (1400 - 1600°F) was unsatisfactory because of the frequent occurrence of troublesome clinker formation. This condition was attributed to the relatively high concentration of iron and aluminum in the sludge and led to deliberate lowering of the combustion zone temperature to between 650°C and 760°C (1200 - 1400°F). As a result of this low furnace operating temperature, the throughput capacity of the incinerators was substantially reduced (50 to 60% of design) and incomplete burnout of sludge was encountered from time to time.

An in-depth pilot-scale experimental program was therefore designed to determine the furnace operating conditions required for incinerating an iron-rich municipal sludge with a minimum of operation problems.

2 DESCRIPTION OF EQUIPMENT

2.1 Pilot-Scale

The layout of the equipment is shown schematically in Figure 1. The pilot-scale incinerator was housed in an unheated wooden enclosure attached to the vacuum filter building. The sludge feeder and weigh belt were located above the incinerator adjacent to the filter cake sludge conveyor.

The pilot unit is an Envirotech BSP pilot-scale multiple-hearth incinerator (Figure 2). It is a natural gas fired furnace consisting of six alternating in and out hearths (0.75 m inside diameter), encased in a refractory lined steel case. The manufacturers rated capacity is 113.5 kg of wet sludge per hour, at 20% total solids and 75% volatile matter. This is equivalent to 50.9 kg of wet sludge per square meter of effective hearth area per hour.

The incinerator was fed by diverting a full day's supply of sludge from the main conveyor, by means of a rubber knife-edge blade, to a storage bin situated above a "Moyno" open-throat progressing cavity pump (type 2J3). The pump delivered the sludge to a K-Tron Feeder System at a rate slightly higher than the programmed rate to the incinerator. No difficulty was experienced pumping the cake (14% to 19% total solids) from Hamilton's vacuum filters, but neither sludges of high solids content (~40%) nor pulp conditioned sludges could be transported by this pump.

To ensure control of the mass flow rate and automatic totalization of sludge throughput to the incinerator, a K-Tron model CF-12 Digi Drive Gravimetric Feeder complete with a paced twin screw prefeeder (K-Tron model TO-35) was used to deliver the sludge cake to the incinerator. The unit had a repeatable accuracy of $\pm$0.25% (at the 95% confidence level) of the set rate based upon 30 consecutive samples.

The exhaust gas from the pilot plant was passed through a cooling chamber where water sprays reduced the temperature of the gas from its exhaust temperature to a water-saturated condition at approximately 93°C (200°F). This greatly reduced the volume of gas before it entered the "Arco" type JS impingement scrubber. The scrubber was designed to operate at a pressure differential of 1.5 kPa (15.2 cm of water) and consisted of three combined stages: 1) the spray section where the large particles

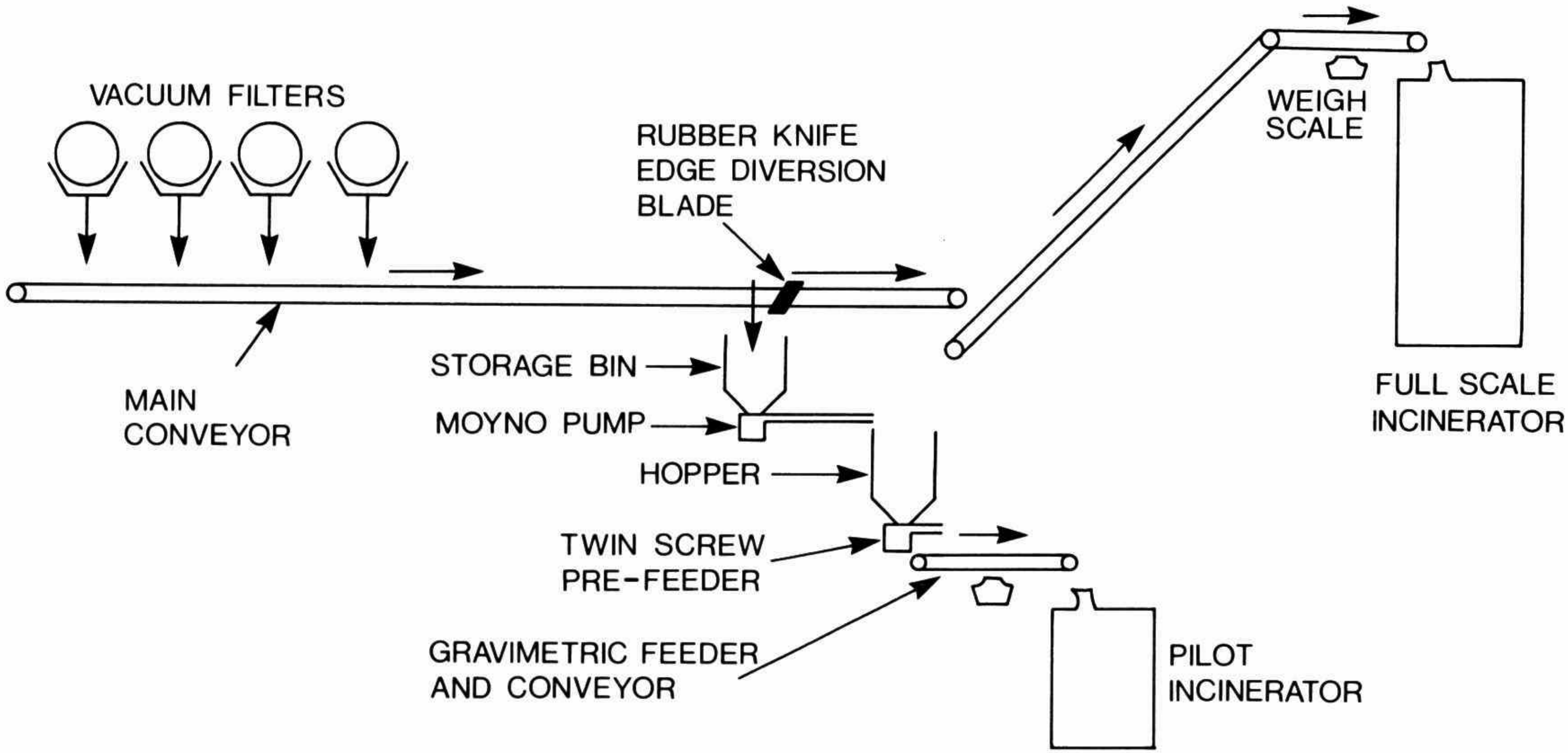

FIGURE 1. SCHEMATIC OF FEED SYSTEM TO PILOT AND FULL SCALE INCINERATORS

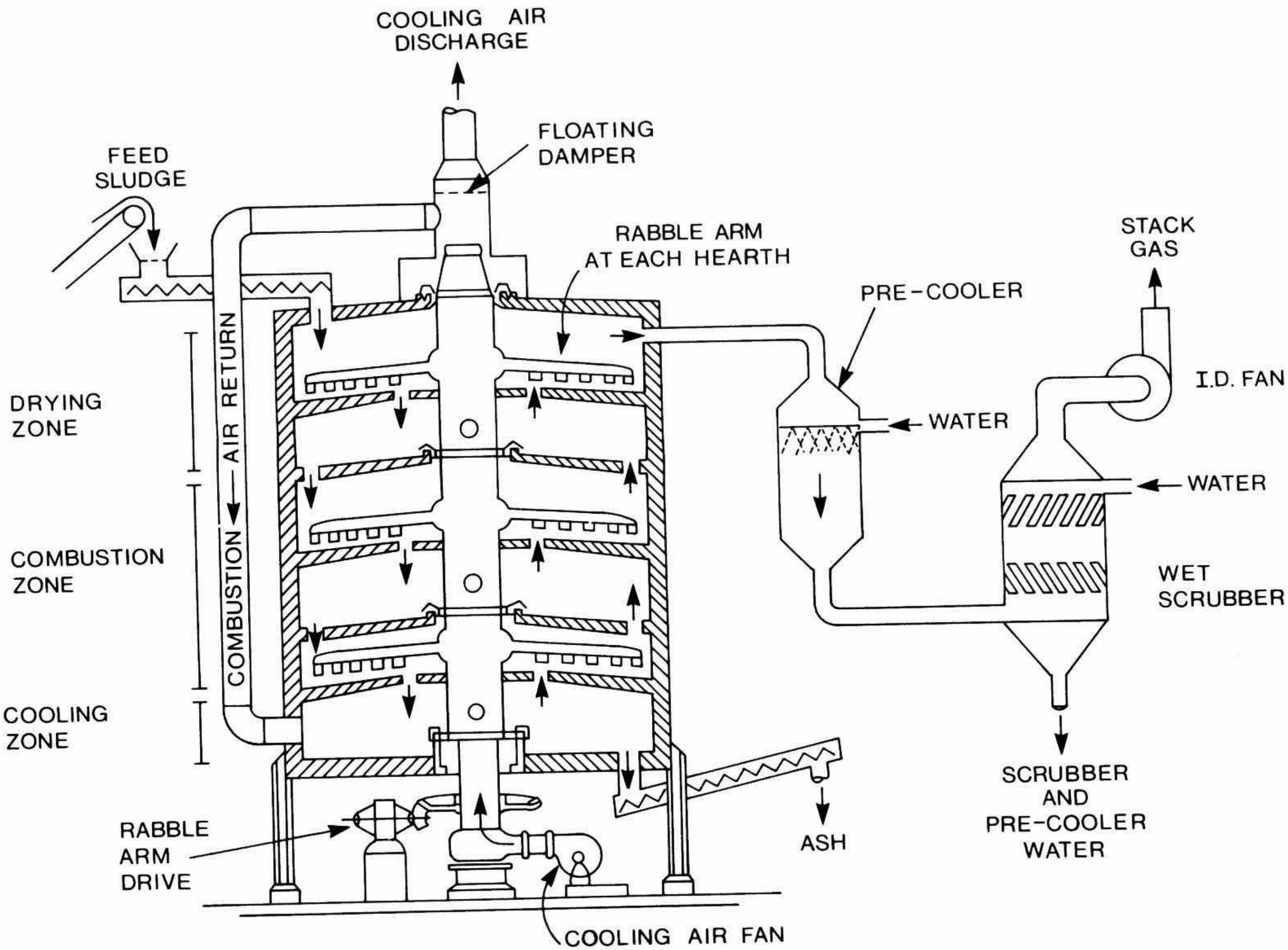

FIGURE 2. PILOT-SCALE MULTI-HEARTH SLUDGE INCINERATOR

were removed and the gases were cooled, 2) the impingement section where the gases were scrubbed and sub-cooled, and 3) the mid-eliminator where the coarse water droplets were removed.

2.2 Full-Scale

The full-scale multiple-hearth incinerators at the Hamilton WPCP are also manufactured by Envirotech BSP. They are fired by natural gas, and have nine alternating hearths (~6 m inside diameter). The manufacturer's rated capacity is 9000 kg of wet sludge per hour at 20% total solids and 75% volatile matter.

The incinerators were fed with vacuum filter cake supplied by conveyors (shown in Figure 1). The total feed to the incinerators was weighed, but the rate was controlled only by the amount of cake produced by the vacuum filters. Typical operating parameters for the full-scale incinerator are shown in Table 1.

TABLE 1. TYPICAL OPERATING PARAMETERS FOR THE FULL-SCALE INCINERATORS AT THE HAMILTON WPCP

Loading Rate (kg/wet sludge/h)	4890
% of Design Loading	54
Centre Shaft Speed (rpm)	1.0
Burning Zone Temperature (°C)	704

Prior to discharge to the stack, the exhaust gases were passed through a wet scrubber which uses secondary effluent. The scrubber water is used to slurry the ash, and the resulting mixture is disposed of as landfill.

3 EXPERIMENTAL PROGRAM

3.1 Experimental Design

The program was designed to evaluate the effect of operating variables on the performance of the pilot-scale incinerator. The operating variables selected were temperature (T), sludge throughput rate (R) and centre shaft speed (S). By arranging these variables in a "factorial" design, the total variation in a data set, i.e., 1) selected elements, 2) residual carbon, 3) operational data, and 4) occurrence of clinker formation, could be reduced to components associated with the operating variables and their relative importance assessed. The levels of each variable were determined in accordance with previously published data and an assessment of current practices, and on the basis of existing resources, manpower and fiscal constraints.

3.2 Evaluation of Operating Variables

The problem of clinker formation at the Hamilton WPCP had generally been attributed to high temperatures in the burning zone and, as previously mentioned, had led to the deliberate lowering of the temperature to a range of 650°C to 760°C. As a result, the burning zone temperature was determined to be the variable of greatest importance, and its effects on a data set were investigated most thoroughly. Five levels were originally chosen to cover the range from 704°C to 928°C in increments of 56°C. Early in the program the lower boundary of 704°C was found to be incompatible with the desired throughput rates because of incomplete burnout, and it was therefore deleted from the experiment.

The throughput rate (feed rate) is a major factor in determining the residence time of the sludge within the furnace. The throughput rates presently used in Ontario range from 50 to 60% of rated capacity at Hamilton, to 120% of design capacity at Toronto Main. The levels of throughput rate selected for this study were in the higher range in order to identify optimum, or boundary, loading conditions. Since it was only feasible to assign three levels to the rate variable, the levels chosen were 90%, 110% and 130% of design, giving rates of 102.2, 124.9 and 147.6 kg per hour of wet sludge.

The centre shaft is a centrally-located cast iron shaft that extends the full height of the furnace and supports cantilevered rabble arms above each hearth. Each arm rotates with the centre shaft, and contains rabble teeth which rake the sludge spirally across each hearth below the rabble arms. Rabbling, which is directly proportional to the speed of the centre shaft, continually: 1) plows up the solids, 2) breaks up the lumps, and 3) exposes the surfaces to heat and oxygen, thereby increasing the rate of drying, combustion and cooling. The average operational speeds range from 0.75 rpm to 1.5 rpm. After determining that bulldozing (when the sludge exceeds the height of the rabble teeth) did not occur at 0.5 rpm with a throughput rate of 130% of design, the levels of centre shaft speed (S) were set a 0.5 rpm, 1.0 rpm and 1.5 rpm.

The factorial design, which consisted of three levels of throughput rate by three levels of centre shaft speed by four levels of temperature, totaled 36 incinerator runs (Table 2). The repetition of each run would not have given adequate return of information for the work required and/or the time expended. However, the homogeneity of sludge and ash samples had in the past plagued the assessment of the effect of the variables on the sets of data. To achieve the desired replication of data sets, each of the experimental incinerator runs was independently sampled twice.

3.3 Sampling Methodology

Sampling was not initiated until the temperature profile of the incinerator had stabilized, which took from two to three and one-half hours, depending on the operating conditions and moisture content of the incoming feed. Once a steady state was achieved, the feed sludge (filter cake), the incinerated ash, and the scrubber water were sampled at three evenly spaced intervals throughout the steady-state period of approximately three hours. The second data set was obtained by simultaneous, but independent, repetition of the sampling process.

A composite sample from each of the three sample points was obtained by combining the three grab samples. The scrubber water sample was forwarded to the laboratory for analysis. Feed-cake samples were analyzed by the Hamilton WPCP laboratory for total solids and total

TABLE 2. EXPERIMENTAL DESIGN

$R_1 S_1 T_1$	$R_1 S_2 T_1$	$R_1 S_3 T_1$
T_2	T_2	T_2
T_3	T_3	T_3
T_4	T_4	T_4
$R_2 S_1 T_1$	$R_2 S_2 T_1$	$R_2 S_3 T_1$
T_2	T_2	T_2
T_3	T_3	T_3
T_4	T_4	T_4
$R_3 S_1 T_1$	$R_3 S_2 T_1$	$R_3 S_3 T_1$
T_2	T_2	T_2
T_3	T_3	T_3
T_4	T_4	T_4

Throughput Rate = R_1, R_2, R_3 = 102, 125, 148 kg wet sludge/h
Centre Shaft Speed = S_1, S_2, S_3 = 0.5, 1.0, 1.5 rpm
Temperature = T_1, T_2, T_3, T_4 = 760, 816, 872, 928°C

volatile solids. The incoming feed cake and the incinerated ash samples were dried at 105°C, ground in a ball mill, and passed through a 80 mesh screen before analysis.

3.4 Analytical Methods

Constituents tested for in the sludge feed, the incinerator ash, and the scrubber water for each experimental run were total phosphorus, total Kjeldahl nitrogen, total sulphur, total carbon, arsenic, cadmium, mercury, nickel, zinc, copper, magnesium, aluminum, calcium, chromium, iron, lead, and silica. All analyses were performed according to the Wastewater Technology Centre, Analytical Methods Manual (1979). The same analyses were carried out on the particulate samples collected during the stack testing program.

4 RESULTS AND DISCUSSION

4.1 Incinerator Feed Characteristics

The sludge used in the incinerator studies was produced at the Hamilton WPCP. It was a mixture of thickened waste activated sludge and digested sludge which had been dewatered on coil vacuum filters. Polymers were used to condition the sludge for filtration and resulted in a filter cake with a total solids content ranging from 14 to 18%. The composition of the vacuum filter cake (i.e., incinerator feed) is presented in Table 3. The values shown for each parameter are the grand means from the 36 experimental runs. The Ontario average values for selected metals (Antonic et al, 1980) are also shown.

The levels of zinc, copper, nickel, chromium, and lead in the Hamilton sludge were significantly higher than the Ontario average. This is consistent with the highly industrial nature of the sewage input to the treatment plant. The level of iron was also relatively high and was in the same range as would be expected for a sewage treated with an iron salt for phosphorus removal (Cohen and Bryant, 1978). The volatile solids content and calorific value compare favourably with those of other mixed digested sludges (Schroeder and Cohen, 1978).

Prior to the initiation of the experimental program, a sampling program was conducted to determine the variability of the sludge. The constituents analyzed were total organic carbon, total Kjeldahl nitrogen (TKN), phosphorus, arsenic, cadmium, copper, magnesium, mercury, nickel, sulphur, and zinc. The sampling program consisted of taking triplicate samples each hour for a six-hour period. These samples were then composited to produce three daily composites. The procedure was repeated for five consecutive days.

Analysis of variance indicated that between-day variation was statistically significant for copper at the 5% level, and for magnesium, nickel and total organic carbon at the 1% level. The day-to-day variation in the other constituents was not statistically significant. The results of this short-term monitoring program (one week) are not necessarily indicative of longer-term trends, since sludge components are also susceptible to seasonal influences. The within-day variation was of lesser concern because an entire day's feed supply for the pilot plant was obtained in approximately 15 minutes from the main conveyor belt.

TABLE 3. FEED SLUDGE CHARACTERISTICS[1]

	Mean[2]	Standard Deviation[2]	Range[2]	Ontario Average (Antonic *et al*, 1980)
Calorific Value[3]	12 345	NA	NA	NA
% Total Solids	15.82	1.102	14.2 - 18.8	NA
% Volatile Solids	45.61	1.333	43.4 - 49.9	NA
Total Carbon	24.78	1.662	22.1 - 29.4	NA
Total Nitrogen	0.26	0.14	0.03 - 0.71	NA
Phosphorus	3.14	0.195	2.8 - 3.7	NA
Aluminum	2.22	0.0717	2.0 - 2.3	NA
Arsenic	2.07×10^{-3}	0.48×10^{-3}	1.5×10^{-3} - 3.9×10^{-3}	NA
Calcium	5.09	0.713	3.8 - 6.4	NA
Cadmium	2.26×10^{-3}	0.23×10^{-3}	1.6×10^{-3} - 3.0×10^{-3}	3.0×10^{-3}
Copper	0.144	0.034	0.098 - 0.29	0.081
Chromium	0.261	0.014	0.23 - 0.30	0.120
Iron	6.97	0.617	6.04 - 8.97	NA
Lead	0.135	0.013	0.10 - 0.16	0.060
Magnesium	1.09	0.150	0.82 - 1.3	NA
Mercury	4.99×10^{-4}	1.26×10^{-4}	3.3×10^{-4} - 14×10^{-4}	NA
Nickel	3.70×10^{-2}	1.22×10^{-2}	0.018 - 0.1	0.017
Silica	7.77	0.625	6.42 - 9.41	NA
Total Sulphur	1.27	0.182	0.98 - 1.7	NA
Zinc	0.604	0.0555	0.64 - 0.76	0.148

[1] Number of samples = 36

[2] Elements as g of element/100 g of dry sludge

[3] kJ/kg of dry solids

NA - Not Available

4.2 End Product Characteristics

The characteristics of the incinerator ash and the scrubber water are presented in Tables 4 and 5, respectively. These values represent the averages from the 36 experimental runs. The fate of the various constituents are discussed in subsequent sections.

The characteristics of the stack gas from the pilot incinerator were determined prior to the actual experimental program. The operating conditions were significantly different (63% of design load and a temperature of 736°C), and the results were not necessarily indicative of what was achieved during the factorially designed experimental program. The results are presented in Table 6 for background information only.

4.3 Fate of Sludge Constituents

4.3.1 General

Analysis of variance was completed for each constituent measured, in order to determine the effect of operating variables on the final fate of the elements. A complete summary of the raw data, including the replicate samples, is presented in Appendix B. A summary of the grand means for the 36 runs, the standard deviations, and the ranges is presented in Table 7. The treatment means are also presented, i.e., the value for T_1 is the average of nine runs for all combinations of three levels of rate and three levels of shaft speed at a constant temperature of T_1.

Two gaps are evident in the data base: mercury measurements in scrubber water and TKN measurements. At the time the experiment was conducted, analytical techniques were not available for the analysis of mercury in the scrubber water. Analysis of the TKN in the feed and ash was completed, and the grand average, standard deviation and mean are presented; but values for treatment means are not shown. Measurement of TKN in these two media resulted in such a wide variation between duplicate samples that no inference could be drawn about the effects of operating variables.

A cursory evaluation of whether an element is conservative (remains in the ash) or volatile (converted to a gaseous form) can be made by comparing the grand means (Table 7) of the concentrations in the feed and the ash. Since the concentration in the feed is in terms of percentage

TABLE 4. ASH CHARACTERISTICS*

Element	Mean**	Standard** Deviation	Range**		
Total Carbon	0.14	0.13	0.005	-	0.6
Total Nitrogen	0.36	0.28	0.05	-	1.1
Phosphorus	6.18	0.4919	5.6	-	7.3
Aluminum	4.14	0.149	3.7	-	4.3
Arsenic	0.00332	0.000604	0.0023	-	0.0049
Calcium	9.70	0.849	8.2	-	11
Cadmium	0.00242	0.000967	0.0006	-	0.0043
Copper	0.271	0.0336	0.22	-	0.34
Chromium	0.477	0.0325	0.41	-	0.56
Iron	13.78	0.8469	11.9	-	16.4
Lead	0.254	0.0359	0.19	-	0.32
Magnesium	2.10	0.152	1.8	-	2.4
Mercury	1.6×10^{-6}	1.6×10^{-6}	0.5×10^{-6}	-	9.0×10^{-6}
Nickel	0.0710	0.0212	0.048	-	0.12
Silica	13.32	1.349	13.3	-	16.5
Total Sulphur	0.964	0.267	0.35	-	1.5
Zinc	1.25	0.0769	1.1	-	1.4

* Number of samples = 36
**g of element/100 g of ash

TABLE 5. SCRUBBER WATER CHARACTERISTICS*

Element	Mean**	Standard** Deviation	Range**		
Total Carbon	35.7	11.07	14.0	-	59.0
Total Nitrogen	25.56	5.41	13.0	-	40.0
Phosphorus	0.350	0.667	5.0×10^{-3}	-	2.8
Aluminum	1.42	0.767	0.43	-	3.9
Arsenic	0.0258	0.126	4.0×10^{-3}	-	1.1
Calcium	44.7	5.97	36	-	62
Cadmium	0.0209	0.00970	5.0×10^{-3}	-	0.045
Copper	0.167	0.107	0.34	-	0.52
Chromium	0.252	0.161	0.05	-	0.85
Iron	6.180	4.165	1.08	-	23.2
Lead	0.442	0.192	0.14	-	1.05
Magnesium	7.70	0.991	6.2	-	9.9
Mercury	NM	NM	--	NM	--
Nickel	0.0521	0.0302	0.01	-	0.16
Silica	2.75	1.17	1.0	-	5.7
Total Sulphur	68.75	34.96	20.0	-	140
Zinc	0.780	0.417	0.20	-	2.4

* Number of samples = 36
**g of element/100 g of ash
NM = Not measured

TABLE 6. STACK GAS CHARACTERISTICS FROM THE PILOT-SCALE INCINERATOR

Parameter	mg/kg of dry feed solids
Particulates	820
Cadmium	1.144
Copper	0.278
Chromium	0.341
Iron	0.647
Lead	8.531
Mercury	3.42
Nickel	0.046
NO_x	5.78×10^3
Sulphur Dioxide	0.047×10^3

of fixed solids (g of element/100 g of fixed solids in the feed), then if the element is conservative, the concentrations in the feed and the ash will be similar. If, however, the concentrations of the element in the feed and the ash are not similar, then the element either is being selectively classified into the stack gas particulates or volatilization is occurring. The rationale is valid, assuming the proportion of fixed solids which volatilize at temperatures above 600°C is relatively small. The mass of fixed solids in the feed is therefore a good approximation of the mass of incinerator ash. The effect of any operating variable on the final distribution of an element can be evaluated by comparing the treatment means of the feed and ash for the operating parameter of interest. For example, in the case of cadmium, a comparison of the grand mean for the feed (4.1×10^{-3}%) and the ash (2.4×10^{-3}%) indicates that considerable cadmium is lost from the ash. Comparing the treatment means for the temperature, the concentration in the ash decreases from 3.0×10^{-3}% at T_1 to 1.9×10^{-3}% at T_4, indicating that the percentage of cadmium volatilized increases with increasing temperature. It is then desirable to complete an analysis of variance to determine if this observed effect is significant.

Table 8 lists the various elements and indicates whether they are conservative or volatile. It also lists the ash/feed ratio of the concentrations and the percentage of each element which is accounted for by a mass balance. The mass balance was completed on a mass-per-hour

TABLE 7. DATA SUMMARY

	$\bar{x}$	σ	Range	T_1	T_2	T_3	T_4	R_1	R_2	R_3	S_1	S_2	S_3
Sludge Feed (kgTS/h)	19.89	2.159	14.8-24.1	20.16	20.11	19.68	19.64	17.30	20.43	21.95	20.02	19.97	19.69
Ash Production (kg/h)	9.17	1.768	2.89-11.75	9.40	9.44	9.36	8.43	7.29	9.38	10.81	8.96	9.48	9.04
(% of Theoretical)	84.69	10.81	28.5-96.1	86.52	86.94	87.44	77.85	81.03	83.90	89.13	81.17	86.67	86.23
(% Retained on 4 mm sieve)	0.888	1.486	0.012-5.7	0.043	0.052	0.40	3.1	0.71	1.15	0.80	1.1	0.82	0.75
Gas Usage (m^3/kg TS)	0.494	0.082	0.342-0.672	0.518	0.484	0.478	0.496	0.467	0.474	0.541	0.474	0.463	0.545
Scrubber Water (L/h)	4865	90.2	4587-5021	4875	4857	4860	4868	4810	4875	4910	4855	4869	4871
Total Dry Solids (%)	15.8	1.102	14.2-18.8	15.9	16.1	15.8	15.9	16.5	16.4	15.0	16.1	16.1	15.5
Volatile Fraction (%)	45.6	1.333	43.4-49.9	45.7	45.5	45.7	45.6	46.8	45.2	44.9	45.1	45.5	46.2
Aluminum F (%)	4.1	0.1302	3.7-4.3	4.1	4.1	4.1	4.1	4.0	4.1	4.1	4.1	4.1	4.1
A (%)	4.1	0.1492	3.7-4.3	4.1	4.2	4.1	4.1	4.0	4.2	4.2	4.2	4.2	4.1
S.W. (mg/L)	1.4	0.7674	0.43-3.9	1.7	1.1	1.4	1.4	1.0	1.3	1.9	1.4	1.3	1.6
Arsenic F (% x 10^{-3})	3.8	0.8821	2.8-7.2	3.5	3.9	3.9	4.0	3.8	3.6	4.0	3.6	4.4	3.5
A (% x 10^{-3})	3.3	0.6043	2.3-4.9	3.5	3.2	3.3	3.3	3.4	3.2	3.4	3.7	3.3	2.9
S.W. (mg/L)	0.026	0.1256	0.004-1.07	0.012	0.013	0.067	0.010	0.056	0.012	0.009	0.007	0.010	0.061
Cadmium F (% x 10^{-3})	4.1	0.4239	2.9-5.6	4.0	4.1	4.2	4.3	4.3	4.0	4.1	4.2	4.2	4.1
A (% x 10^{-3})	2.4	0.9670	0.6-4.3	3.0	2.7	2.0	1.9	1.8	2.5	2.9	2.6	2.4	2.3
S.W. (mg/L)	0.021	0.009695	0.005-0.045	0.016	0.020	0.023	0.025	0.027	0.020	0.015	0.024	0.022	0.017
Calcium F (%)	9.4	1.307	7.0-11.8	9.3	9.4	9.3	9.3	8.1	9.1	10.9	9.5	9.4	9.2
A (%)	9.7	0.8494	8.2-11.0	9.7	9.6	9.8	9.7	8.9	9.7	10.6	9.9	9.6	9.7
S.W. (mg/L)	45	5.97	36-62	46	43	45	45	41	44	49	45	44	45

TABLE 7. (CONT'D)

	$\bar{x}$	σ	Range	T_1	T_2	T_3	T_4	R_1	R_2	R_3	S_1	S_2	S_3
Total Carbon													
F (%)	45.6	3.055	40.6-54.3	45.5	45.4	45.7	45.6	48.7	44.2	43.8	44.5	45.0	47.2
A (%)	0.3	0.2827	0.05-1.1	0.57	0.43	0.24	0.19	0.36	0.28	0.43	0.32	0.45	0.30
S.W. (mg/L)	35.2	11.07	14.0-59.0	39.8	37.8	31.8	31.3	28.5	35.5	41.4	35.4	33.7	36.4
Chromium													
F (%)	0.48	0.02531	0.43-0.56	0.48	0.48	0.48	0.48	0.50	0.47	0.47	0.48	0.48	0.48
A (%)	0.48	0.0325	0.41-0.56	0.49	0.48	0.48	0.48	0.51	0.45	0.47	0.48	0.48	0.48
S.W. (mg/L)	0.25	0.1609	0.05-0.85	0.33	0.20	0.24	0.24	0.18	0.24	0.34	0.23	0.22	0.31
Copper													
F (%)	0.26	0.06195	0.18-0.53	0.30	0.26	0.25	0.25	0.27	0.25	0.27	0.26	0.28	0.25
A (%)	0.27	0.0336	0.22-0.34	0.26	0.27	0.28	0.28	0.25	0.27	0.30	0.27	0.28	0.27
S.W. (mg/L)	0.17	0.1072	0.34-0.52	0.21	0.13	0.17	0.16	0.10	0.16	0.24	0.16	0.15	0.19
Iron													
F (%)	12.8	1.134	11.1-16.5	13.1	12.5	12.5	13.1	13.3	12.7	12.5	13.0	12.7	12.9
A (%)	13.8	0.8469	11.9-16.4	13.9	13.5	13.8	13.9	14.0	13.9	13.5	14.2	13.5	13.6
S.W. (mg/L)	6.2	4.165	1.08-23.2	8.0	4.8	6.2	5.7	4.2	5.7	8.6	5.8	5.5	7.3
Lead													
F (%)	0.25	0.02474	0.19-0.30	0.24	0.24	0.25	0.25	0.25	0.25	0.25	0.25	0.24	0.25
A (%)	0.25	0.03587	0.19-0.32	0.26	0.25	0.25	0.25	0.23	0.25	0.29	0.25	0.26	0.25
S.W. (mg/L)	0.44	0.1921	0.14-1.05	0.36	0.33	0.50	0.57	0.48	0.41	0.44	0.50	0.43	0.40
Magnesium													
F (%)	2.0	0.2745	1.5-2.4	2.0	2.0	2.0	2.0	1.7	2.1	2.3	2.1	2.0	2.0
A (%)	2.1	0.1524	1.8-2.4	2.1	2.1	2.1	2.1	1.9	2.1	2.3	2.1	2.1	2.1
S.W. (mg/L)	7.7	0.9906	6.2-9.9	7.7	7.4	8.0	7.7	7.0	7.7	9.4	7.5	7.6	8.1
Mercury													
F (% x 10^{-4})	9.2	2.307	6-26	9.7	8.9	9.3	8.8	9.4	9.8	8.3	8.6	8.8	10.0
A (% x 10^{-6})	1.6	1.632	0.5-9.0	2.5	1.1	1.3	1.6	2.1	1.4	1.4	1.9	1.7	1.3
S.W. (mg/L)	--	--	--	--	--	--	--	--	--	--	--	--	--
Nickel													
F (% x 10^{-2})	6.8	2.236	3.4-18.5	6.7	6.6	6.7	7.3	9.2	5.8	5.6	6.3	6.7	7.5
A (% x 10^{-2})	7.1	2.117	4.8-12.0	6.9	7.1	7.2	7.2	9.6	6.1	5.6	6.3	6.7	7.4
S.W. (mg/L)	0.052	0.03021	0.01-0.160	0.067	0.043	0.049	0.049	0.048	0.042	0.066	0.053	0.043	0.060

TABLE 7. (CONT'D)

	$\bar{x}$	σ	Range	T_1	T_2	T_3	T_4	R_1	R_2	R_3	S_1	S_2	S_3
TKN													
F (%)	0.49	0.26	0.056-1.31	--	--	--	--	--	--	--	--	--	--
A (%)	0.14	0.13	0.005-0.6	--	--	--	--	--	--	--	--	--	--
S.W. (mg/L)	25.6	5.412	13.0-40.0	27.1	26.8	24.1	24.2	23.0	27.2	26.5	25.1	25.3	26.1
Total P													
F (%)	5.8	0.3577	5.1-6.8	5.8	5.7	5.8	5.9	6.0	5.9	5.6	5.6	5.8	6.0
A (%)	6.2	0.4192	5.6-7.3	6.1	6.1	6.2	6.4	6.5	6.1	6.0	6.0	6.1	6.5
S.W. (mg/L)	0.35	0.6666	0.005-2.8	0.22	0.21	0.26	0.71	0.86	0.12	0.074	0.58	0.066	0.4
Silica													
F (%)	14.3	1.150	11.8-17.3	14.5	14.3	14.2	14.2	14.1	14.1	14.4	15.1	14.1	13.7
A (%)	13.3	1.349	11.3-16.5	13.4	13.1	13.3	13.4	14.6	13.0	12.4	13.9	13.3	12.8
S.W. (mg/L)	2.7	1.167	1.0-5.7	3.1	2.3	2.9	2.7	2.1	2.7	3.5	2.7	2.5	3.1
Total S													
F (%)	2.3	0.3349	1.8-3.1	2.4	2.3	2.3	2.3	2.8	2.1	2.1	2.4	2.3	2.3
A (%)	0.9	0.2667	0.35-1.5	1.2	1.1	0.88	0.62	0.92	0.99	1.0	0.99	0.98	0.92
S.W. (mg/L)	69	34.96	20-140	58	63	74	80	96	66	44	52	67	83
Zinc													
F (%)	1.1	0.1017	1.0-1.4	1.1	1.1	1.1	1.1	1.2	1.1	1.1	1.1	1.1	1.1
A (%)	1.2	0.0769	1.1-1.4	1.2	1.2	1.3	1.3	1.3	1.2	1.2	1.3	1.2	1.2
S.W. (mg/L)	0.78	0.4166	0.2-2.4	0.91	0.59	0.78	0.84	0.60	0.70	1.0	0.73	0.73	0.89

$\bar{x}$ = grand mean of 36 runs
σ = standard deviation
T_1-T_4 = temperature treatment means
R_1-R_3 = feed rate treatment means
S_1-S_3 = centre shaft speed treatment means
F (%) = concentration of element in feed sludge as a weight percent of the total fixed solids
A (%) = concentration of element in the ash as a weight percent of total solids
S.W. (mg/L) = concentration of element in the scrubber water in mg/L
*NOTE - See Table 2 for operating variable levels.

TABLE 8. FATE OF SLUDGE CONSTITUENTS

Element	Conservative	Volatile	% Accounted for by Mass Balance[a]	Ratio of Concentrations Ash/feed
Total Phosphorus[b]	x		90.2	1.07
Zinc[b]	x		98.4	1.13
Iron	x		93.0	1.07
Magnesium	x		106.0	1.05
Aluminum	x		87.7	1.02
Nickel[b]	x		90.4	1.04
Copper[b]	x		90.1	1.03
Calcium	x		109.4	1.04
Chromium[b]	x		86.1	0.99
Lead	x		95.7	1.03
Silica	x		79.8	0.93
Total Carbon		x	4.1	0.008
Sulphur		x	34.9[c]	0.41
Cadmium[b]		x	74.7	0.58
Mercury[b]		x	0.2[c]	0.002
Arsenic[b]		x	103.6	0.87

[a]Mass balance does not include stack gas

[b]Discussed in detail in text

[c]Does not include scrubber water

basis and includes the feed, ash, and scrubber water. The fact that an element is volatile does not necessarily mean that it is lost to the atmosphere. Depending on the element, various amounts may be recovered in the scrubber water. For example, using the grand means for cadmium, approximately 42% of the 0.218 g/h that is lost between the feed and the ash is recovered in the scrubber water.

4.3.2 Phosphorus

The fate of phosphorus in the incineration process is of direct concern as it relates to the Province of Ontario phosphorus removal program. A study was conducted by the Ministry of the Environment (Archer, 1976) to determine the amount of phosphorus that would be released in stack emissions. Although sampling was only carried out over one day, the results showed that greater than 99% of the total phosphorus contained in the digested sludge remained in the incinerator ash.

The assessment of the data set, over the boundary constraints of this study, support the findings of Archer (1976). Phosphorus is a conservative element which exhibits no significant disproportionation nor classification due to volatilization, but remains as a refractory compound in the ash.

4.3.3 Chromium, nickel, copper

Inspection of the data sets reveals that the variation of operating parameters has no effect on the concentration of these elements in the ash and that there is no interaction between the parameters. The apparent effect of feed rate on the concentrations of chromium and nickel in the ash is due to the non-random application of the experimental program. Levels of temperature and centre shaft speed were randomized with regard to time, but feed rate was not. Correlation of the concentrations in the feed and the ash reveals that the effect is due to changes in the sludge (Figure 3) over the time-frame of the study, rather than to the feed rate.

The concentration of copper in the feed does not exhibit any trend as a function of time (Figure 3). However, the concentration in the ash shows an underlying tendency to increase with increasing feed rate. Since the feed rate will affect the residence time of the sludge within the furnace, it is possible that at the low feed rates (higher residence

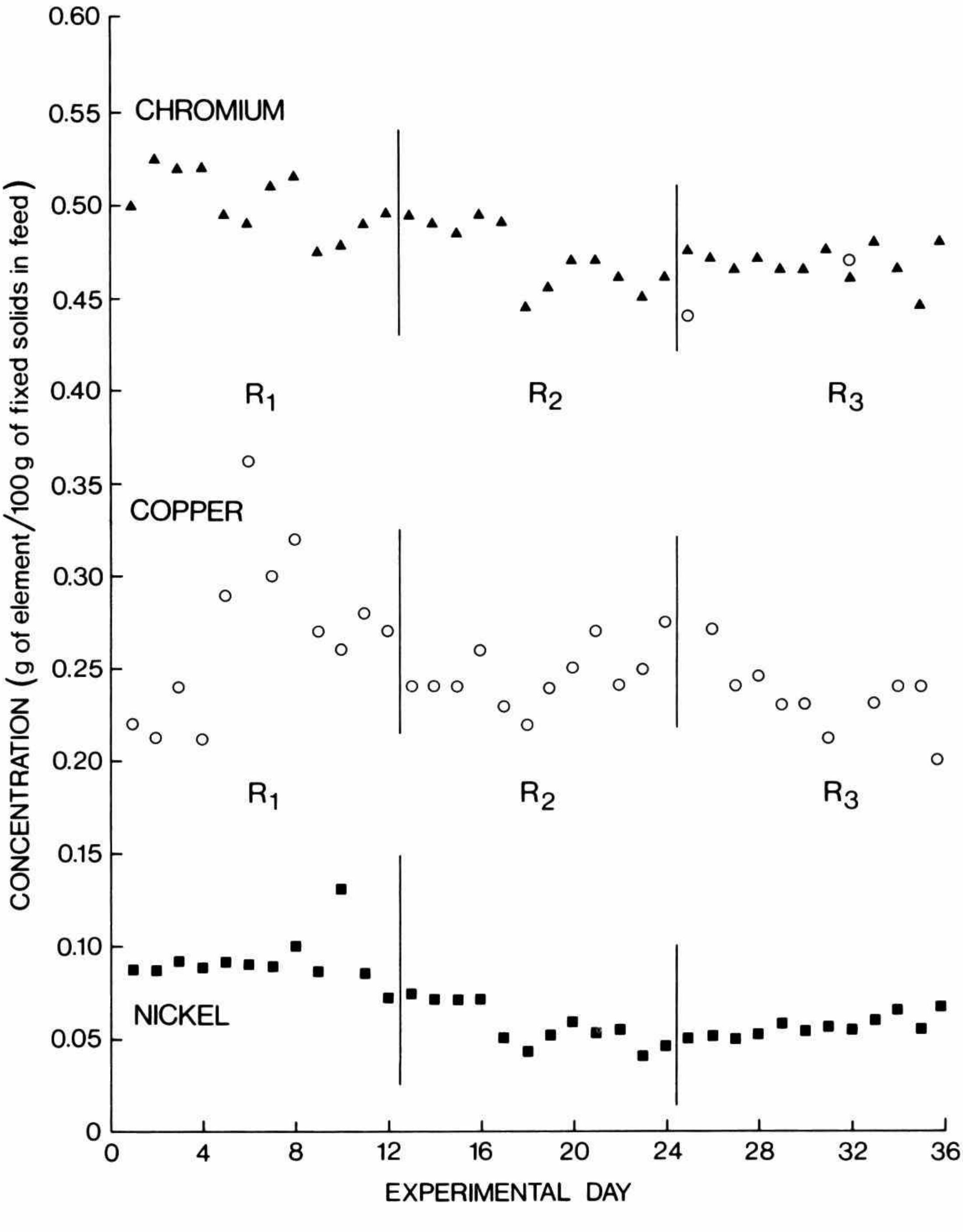

FIGURE 3. VARIATIONS OF Cr, Cu, AND Ni IN FEED SLUDGE AS A FUNCTION OF TIME

times) the change is due either to formation of a refractory compound or to classification into the fly ash. The shaft speed also affects residence time, but no change of copper in the ash is evident with varying shaft speeds. Since the concentration of copper in the ash shows a net gain of 2.5%, and since the range of concentration of copper from the lowest to the highest feed rate is within one standard deviation of the grand mean, it is unlikely that the effect is real.

4.3.4 Lead, zinc

During incineration, the potential exists for the release of significant amounts of heavy metals to the atmosphere. Several researchers (Farrell and Salotto, 1973; Matsui and Hiraoka, 1974; Van Loon, 1976) have expressed concern, based on both indirect and direct evidence, that large amounts of metals such as arsenic, cadmium, lead, zinc, and mercury may be either classified into the fly ash or volatilized and subsequently discharged to the atmosphere.

Assessment of the data set reveals that, with respect to lead and zinc, this concern is unfounded. The systematic increase of temperature from 760°C to 928°C in the factorial design had no effect on the concentration of lead in the ash. The statistically more important variable is the feed rate, where the data reveal an underlying tendency for lead to classify at the lower feed rates, presumably because of the longer residence time within the furnace. However, since the actual magnitude of the deviation from the grand mean (less than one standard deviation) for the lowest feed rate is so small, it is unlikely that the effect is real. The concentration of lead in the ash shows a net gain of 2.7% compared to the feed. This gain is insignificant at the 5% level of significance. A mass balance (Table 8) accounts for 96% of the lead input to the system, and 99.6% of this is found in the ash and scrubber water. Within the constraints of the experiment, the operating variables are independent of each other and do not affect the final distribution of the lead. Lead exhibits no disproportionation or classification due to volatilization, but remains in the ash.

Similarily, the operating variables had no significant effect on the concentration of zinc in the ash. The apparent effect of the feed rate is again due to changes in the feed sludge with respect to time

(Figure 4) and the fact that feed rate was not randomized throughout the experimental program. The concentration of zinc in the ash is significantly greater (by 12.7%) than in the feed sludge and may be due to the breakdown of sand and clay. The highest concentrations are found at the lowest feed rate, indicating that the residence time is a contributing factor. A mass balance (Table 8) accounts for 98.4% of the input zinc, with 99.98% of this found in the ash and scrubber water. Zinc did not exhibit any disproportionation or classification due to volatilization.

4.3.5 Cadmium

Analysis of the data set indicates that a significant proportion of the cadmium is lost during incineration. At a temperature of 760°C approximately 25% of the cadmium in the feed sludge has been classified by volatilization into the gas stream, and this trend accelerates as the temperature increases (Figure 5). On a mass balance basis, at 760°C approximately 65% of the cadmium introduced is retained in the ash and 18% is recovered in the scrubber water, leaving 17% unaccounted for and presumably lost to the atmosphere. By comparison, at 928°C only 34% is found in the ash, 27% is recovered in the scrubber water, and 39% is unaccounted for.

4.3.6 Mercury

Due to the inability to measure mercury in the scrubber water during the experiment, the final fate of mercury was not established. Analysis of the data shows that under all conditions, more than 99% is classified into the gas stream. The proportion recovered in the scrubber was not determined. The importance of this problem is, however, put into perspective by estimates presented by U.S. EPA (1972). Without considering recovery in the scrubber, it was estimated that 36 kg of mercury would be released to the atmosphere per day through the burning of sludge in the United States. This compares to an estimate of 2 700 000 kg per day of mercury that is discharged into the atmosphere from the burning of coal.

4.3.7 Arsenic

A comparison of the arsenic levels in the feed sludge and in the ash shows the differences to be statistically significant and indicates that arsenic is being classified into the gas stream. On the basis of a

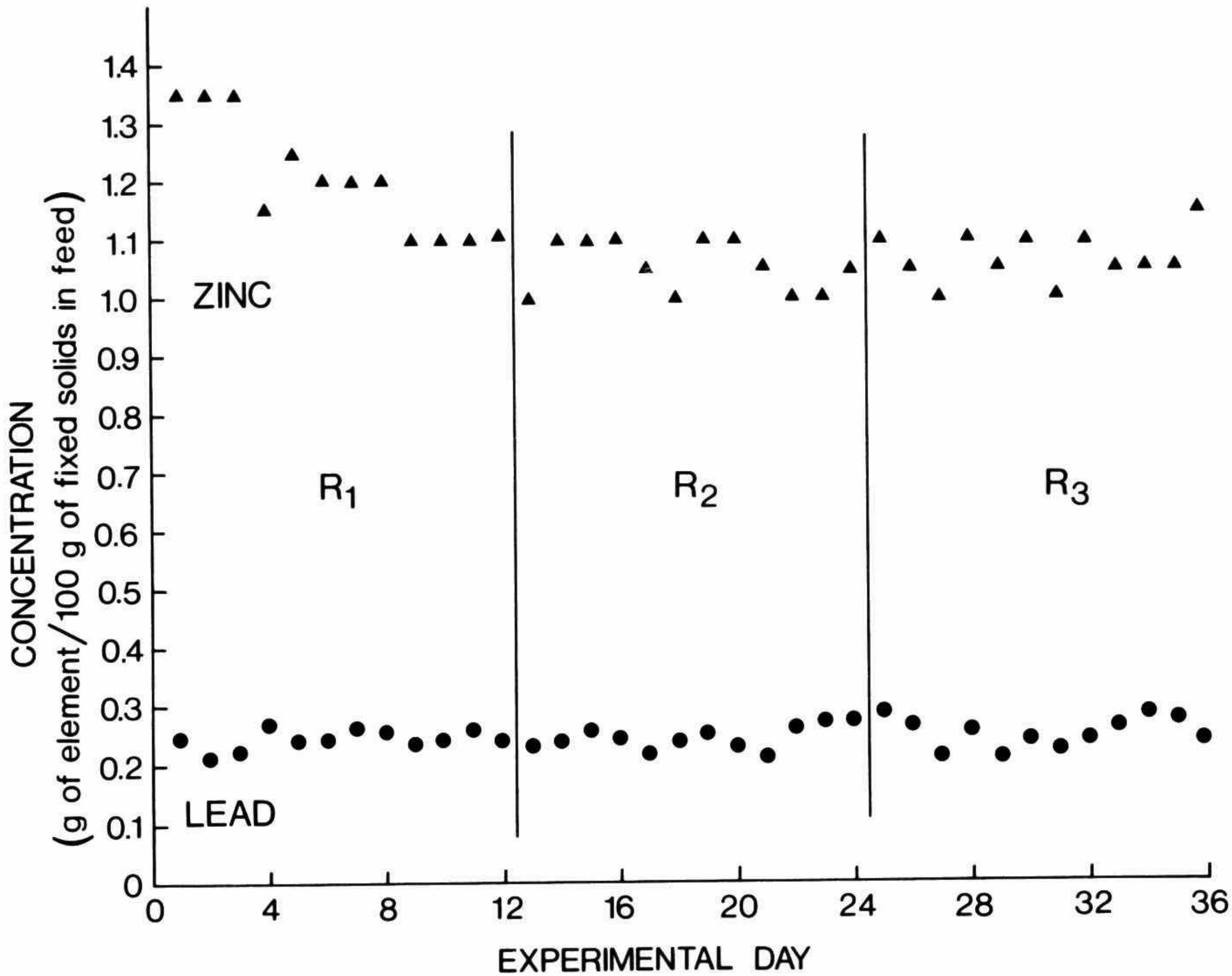

FIGURE 4. VARIATIONS OF Zn AND Pb IN FEED SLUDGE AS A FUNCTION OF TIME

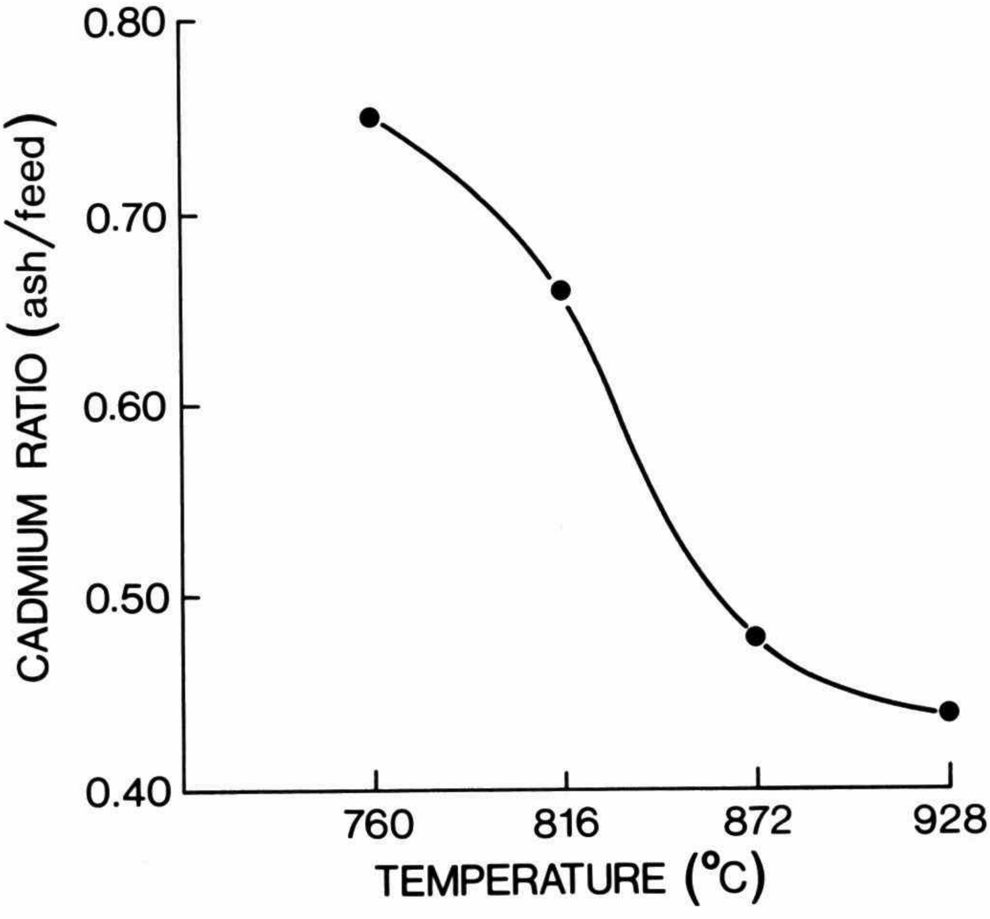

FIGURE 5. EFFECT OF TEMPERATURE ON CADMIUM CONCENTRATION IN THE ASH

mass balance, 26% of the arsenic in the feed sludge is lost to the stack gas, but is not discharged to the atmosphere. When the arsenic in the scrubber water is included, the mass balance, on the grand average, accounts for 103% of the input.

4.4 Effect of Operating Variables on Incinerator Performance

4.4.1 Clinker formation

The reason for lowering the operating temperature in the Hamilton incinerators was to avoid the problem of clinker formation, which was attributed to a combination of the high temperature and the high iron content of the sludge. This was accomplished at the expense of lower throughput capacity and occasional incomplete burnout. The criteria used to evaluate the effect of operating variables on clinker formation in the pilot-scale incinerator and to predict the conditions under which it would occur were:

1) The measured ash production was expressed as a percentage of the theoretical ash production. This would identify situations where clinkers were sufficiently large to lodge within the pilot-scale incinerator.
2) The percentage by weight of ash particles retained on a 4-mm sieve was determined. An increase in this percentage would indicate that some fusion of the materials is occurring and may signal the beginning of clinker formation.
3) Visual observation of the burning hearths was carried out by the operator.

The data sets for the ash production and sieve tests were not replicated and the second-order effects were used to estimate the error mean square, i.e., the residual variance.

The interpretation of the analysis of variance would lead to the conlusion that the operational variables over the limit of the experiment have no effect on the percentage of ash produced. However, clinker formation was visually observed in two of the runs, and the ash production figures for these two runs confirm the fact. At the highest temperature (928°C) and the lowest feed rate and centre shaft speed -- i.e., the longest residence time -- the ash production was only 28.5% of the

theoretical value. The same effect was evident at the middle level of centre shaft speed (same temperature and feed rate), but was not as pronounced with 69.2% of the theoretical production. Although it is evident that high temperature is an essential factor in clinker formation, it appears that the residence time of the sludge in the furnace is of at least equal concern. At the shorter residence times -- i.e., higher throughput rate and centre shaft speed -- no problems were encountered with the incinerator operating at the 928°C temperature level.

The data with regard to the percentage by weight of particles retained on a 4-mm sieve shows the same trends, but are not as conclusive. This may be due in part to two factors: the selection of 4 mm as the screen size was arbitrary, and the ash sample collected from the two runs where large clinkers were evident in the furnace would not be representative of the complete run. An analysis of the data set shows that the maximum weight fraction retained was 5.7%. Examination of Table 7 shows a tendency for the fraction retained to increase as the temperature increases and the centre shaft speed decreases. This would indicate that this combination of conditions is sufficient to initiate the fusing of iron and aluminum salts, and may be considered a limiting condition for furnace operation. If high temperature (928°C) operation is desirable, then it would appear that clinker formation can be avoided by ensuring a short residence time within the furnace, i.e., high throughput rate and centre shaft speed.

4.4.2 Carbon destruction

One of the major considerations in the operation of a sewage sludge incinerator is the removal or destruction of carbon. The residual carbon in the ash is a measure of the effectiveness of the combustion process and will identify a limiting condition for operation. The parameter normally used for evaluation is organic carbon, but due to analytical problems encountered during the experiment, the data set chosen in this case was total carbon.

The main operating variables (temperature, feed rate, and centre shaft speed) had a highly significant effect on the concentration of total carbon remaining in the ash. Since the second-order interactions were all highly significant, it would not be valid to discuss the main effects

without further examination of the interactions. Consideration of the absolute magnitudes of total carbon remaining in the ash (Table 7) reveals that this is not necessary. Although the highest residual (0.57%) did occur at the lowest temperature, this represents, on the average, a destruction of 98.7% of the total carbon introduced in the feed. The levels of organic carbon in the ash, while not measured, would obviously be still lower. Under all combinations of temperature and centre shaft speed, it was possible to feed the pilot-scale incinerator at 130% of the design capacity and accomplish at least 98.7% destruction of total carbon. For all practical purposes, burnout was complete over the entire range of the experimental program.

4.4.3 Auxiliary fuel consumption

The sludge cake from the vacuum filters at the Hamilton Water Pollution Control Plant had an average total solids content of 15.8%, of which 45.6% were volatile, and a calorific value of approximately 12 400 kJ/kg of dry solids. Since the sludge contains insufficient energy to evaporate the moisture, auxiliary fuel is required for incineration. The data set for auxiliary fuel consumption was not replicated. Each measurement represented the total fuel consumed during the steady-state period of the test.

Analysis of variance revealed that the variation of temperature over the range tested had no significant effect on the consumption of natural gas, and that temperature acted independently on both the feed rate and the centre shaft speed.

The analysis of variance also revealed an interaction between throughput rate and centre shaft speed. This interaction is shown graphically in Figure 6. In the absence of interaction, one would expect all three levels of R to follow the same trend (curves would have same shape) on moving from S_1 to S_3, which is not the case. Two alternative explanations for the data are possible: Either 1) there is, in fact, a tendency for the gas consumption to increase as the feed rate and/or centre shaft speed increase, or 2) an underlying effect due to some characteristic of the source sludge has introduced a bias into the experiment.

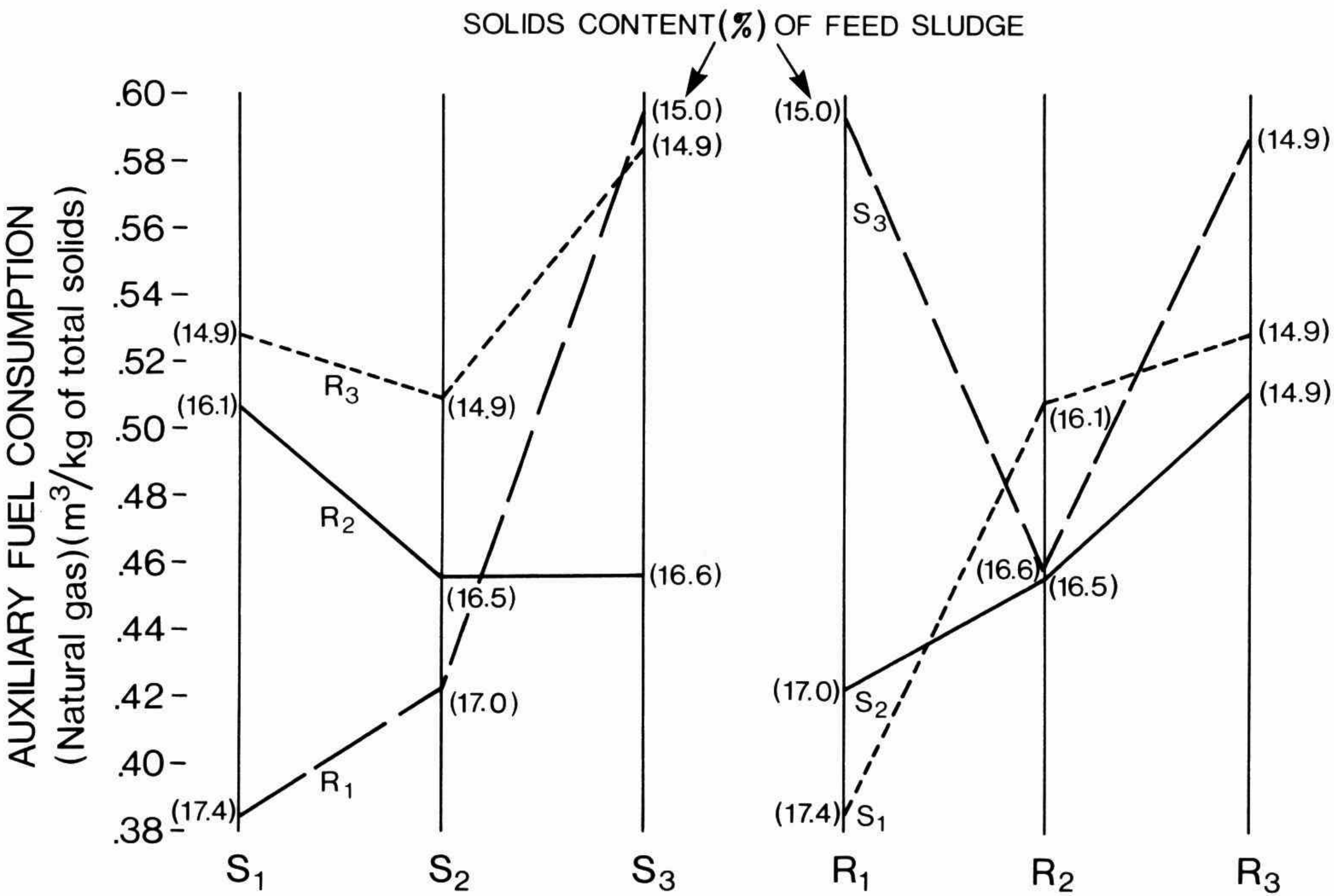

FIGURE 6. GRAPHICAL REPRESENTATION OF THE INTERACTION BETWEEN SLUDGE FEED RATE (R) AND CENTRE SHAFT SPEED (S)

Technically, there is no reason to expect that gas consumption (m^3/kg of dry solids) would increase with increasing feed rate or centre shaft speed, unless there was an accompanying decrease in efficiency. So one must look for an underlying bias. Assigning the total solids contents to the individual runs (Figure 6), shows that the experiment was biased because of the correlation between the natural gas consumption and the total solids of the source sludge. Thus the effect of varying water content in the sludges is of a sufficiently large magnitude to mask any conclusions that might be drawn as to the effect of either feed rate or centre shaft speed on gas consumption.

To further investigate this effect, the gas consumption was plotted against the total solids content of the sludge (Figure 7) and a linear regression analysis completed. The observed value of 0.6585 for the correlation coefficient (r) with 34 degrees of freedom is highly significant. However, since "r" explains only 42% of the variation of y (gas consumed/kg of total solids) through its relationship with x (% total solids of sludge), the regression equation does not give a precise estimate of y. Extrapolating, sludges with a solids content of 25.9% would theoretically burn without the use of auxiliary fuel, but in order to predict with confidence (95%) the point of autogenous combustion, a sludge with a solids content in excess of 30.9% would be required.

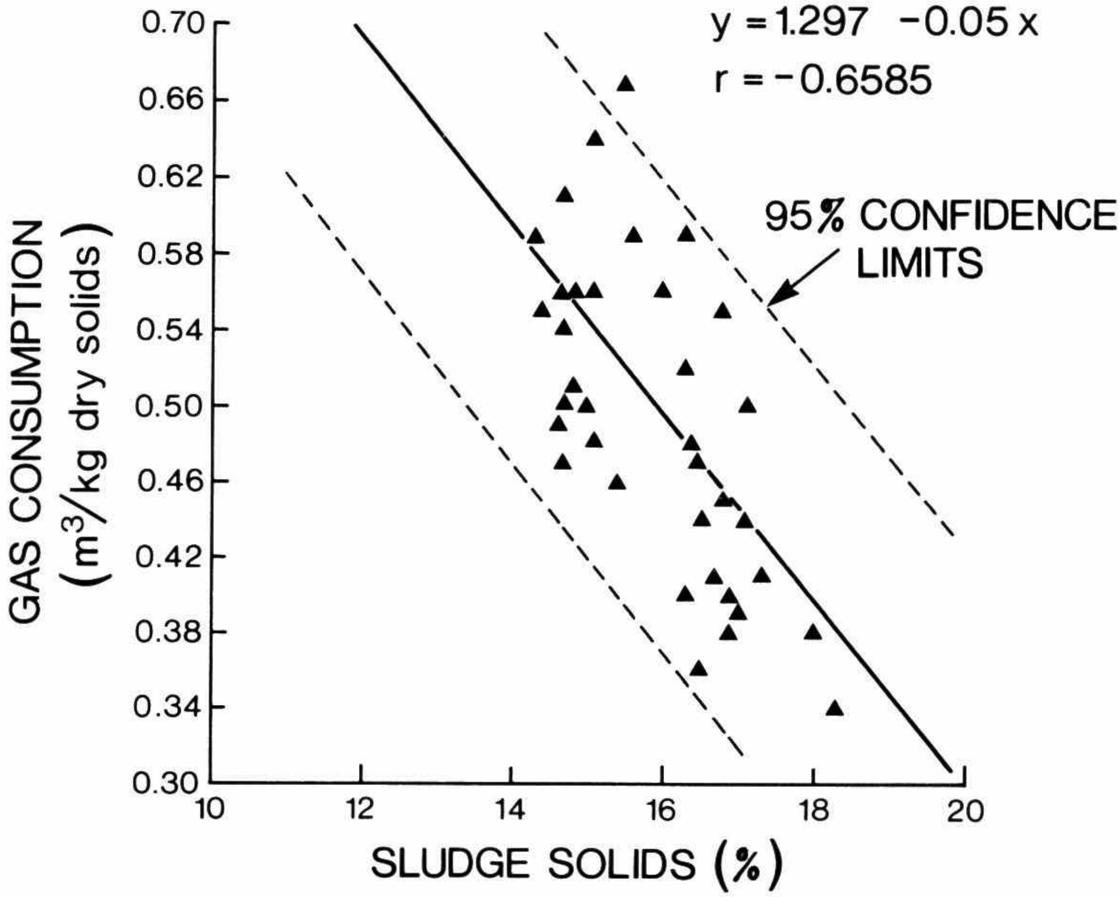

FIGURE 7. EFFECT OF SLUDGE SOLIDS CONCENTRATION ON AUXILIARY FUEL CONSUMPTION

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APPENDIX A

SLUDGE SOURCES AND TYPES - C.F.B. BORDEN

TABLE A-1. SLUDGE SOURCES AND TYPES (Schroeder & Cohen, 1978)

Sludge Source	Type of Sludge	Chemical(s) Added		Dewatering Method
		Phosphorus Removal*	Sludge Conditioning**	
CFB Borden	PR ND	Lime, 150 - 250 mg/L	---	DB
Hamilton	PR + WAS AN D Iron-Rich	Before implementation	Polymer, 0.1 - 0.3%	VF
Toronto Main	PR + WAS AN D	Before implementation	Polymer, 0.5 - 0.7%	VF
Windsor West	PR ND	Alum, 88 mg/L Polymer, 0.3 mg/L	Ferric Chloride, 0.4 - 1% Lime, 10 - 15%	VF
Windsor Little River	PR + WAS ND ND	Alum, 65 mg/L	Polymer, 0.1 - 0.2%	C
London Greenway	PR + WAS ND	Before implementation	Ferric Chloride, 1.2 - 5.3% Lime, 13.5 - 30%	VF
London Pottersburg	PR + WAS ND	Ferric Chloride, 16 - 19 mg/L	Ferric Chloride, 2.4 - 4.9% Lime, 19 - 36%	VF
Mississauga Lakeview	70% PR (ND) + 30% (PR + WAS) (AN D)	Before implementation	Thermal Conditioning by Wet Air Oxidation (LPO)	VF

* dosage expressed as weight of chemical added per unit volume of wastewater.
**dosage expressed as percent by weight of dry solids.

ND - no digestion
AN D - anaerobic digestion
PR - primary sludge
WAS - waste activated sludge

VF - vacuum filter
C - centrifuge
DB - drying bed
LPO - low pressure oxidation

APPENDIX B

RAW DATA

TABLE B-1. OPERATIONAL DATA

CODE - abc	-	a = temperature level 1 to 4 b = feed rate level 1 to 3 c = shaft speed level 1 to 3
Feed Rate	-	feed rate to the incinerator (kg of dry sludge solids/h)
Ash Production	-	kg/h
	-	% THEO (% of theoretical ash production based on fixed solids in the feed)
Gas Used	-	unit gas consumption (m^3 of gas consumed/kg of dry sludge solids in the feed)
Scrubber Water	-	flow rate to be scrubber (L/H)

TABLE B-1. OPERATIONAL DATA

	FEED RATE	ASH PRODUCTION		GAS USED	SCRUBBER WATER
CODE	KG./H	KG./H	%THEO	M3/KG.	L/H
abc					
111	18.25	8.63	86.32	.41	4841.00
211	17.44	8.41	87.66	.38	4865.00
311	17.73	8.09	84.69	.40	4587.00
411	18.78	2.89	28.54	.34	4904.00
121	18.81	8.92	87.24	.56	4875.00
221	20.67	9.71	84.86	.36	4819.00
321	21.05	9.69	83.19	.55	4879.00
421	19.89	9.02	81.49	.56	4728.00
131	22.52	10.02	80.80	.59	5021.00
231	21.89	11.44	94.38	.56	4879.00
331	21.74	10.74	89.71	.47	4932.00
431	21.51	10.06	85.15	.49	4932.00
112	17.52	8.57	90.31	.44	4940.00
212	18.30	8.45	86.08	.38	4671.00
312	16.76	8.67	96.10	.40	4846.00
412	17.07	6.21	69.15	.47	4849.00
113	18.13	7.26	88.27	.67	4773.00
213	17.69	6.49	80.82	.64	4932.00
313	15.15	6.61	86.12	.50	4736.00
413	14.79	7.26	88.27	.56	4773.00
122	19.22	9.48	89.69	.46	4932.00
222	21.40	9.79	81.54	.50	4864.00
322	20.80	9.41	81.12	.41	4932.00
422	20.85	9.67	84.37	.45	4932.00
123	20.65	9.38	85.18	.44	4773.00
223	21.23	9.28	81.08	.39	4910.00
323	20.34	9.22	83.65	.52	4945.00
423	20.27	9.15	83.44	.47	4910.00
132	22.19	10.69	83.38	.50	4784.00
232	21.42	11.13	95.73	.54	4809.00
332	22.25	10.94	90.42	.48	4932.00
432	21.89	10.91	92.18	.51	4932.00
133	24.12	11.75	87.47	.59	4932.00
233	20.97	10.39	90.32	.59	4964.00
333	21.26	10.98	91.99	.55	4950.00
433	21.67	10.81	88.09	.61	4849.00

TABLE B-2. FEED SLUDGE

CODE - abcd	-	a = temperature level 1 to 4
		b = feed rate level 1 to 3
		c = shaft speed level 1 to 3
		d = sample number 1 to 2
TS	-	total solids (%)
TVS	-	volatile solids fraction (%)

All other elements expressed as % of fixed solids, i.e. g of element/100 g of fixed solids in the feed sludge

TP	-	total phosphorus
TKN	-	total Kjeldahl nitrogen
TC	-	total carbon

TABLE B-2. FEED SLUDGE

CODE abcd	TS	T/S	TP	TKN	S	TC	AS	CD	HG	NI
1111	17.3	44.9	5.6	0.16	3.0	45.4	.0033	.0041	.0008	.082
1112	17.3	45.5	5.3	0.29	2.7	46.1	.0028	.0042	.0009	.092
2111	16.9	44.9	5.4	0.16	2.8	45.0	.0031	.0046	.0008	.082
2112	16.9	45.1	5.5	0.18	3.0	45.2	.0042	.0045	.0008	.091
3111	16.9	45.9	5.4	0.18	3.0	46.8	.0037	.0044	.0009	.092
3112	16.9	45.3	5.5	0.18	2.7	45.7	.0033	.0045	.0010	.092
4111	18.8	46.0	5.7	0.56	2.7	46.5	.0032	.0042	.0008	.093
4112	17.8	45.1	5.3	0.35	3.1	46.4	.0035	.0041	.0007	.083
1211	15.1	45.4	5.7	0.66	2.1	43.8	.0037	.0042	.0009	.053
1212	15.1	45.9	5.5	0.52	2.1	44.2	.0037	.0037	.0008	.054
2211	16.4	44.7	5.6	0.52	2.2	49.0	.0036	.0045	.0010	.051
2212	16.7	44.7	5.4	0.38	2.0	43.3	.0034	.0038	.0009	.060
3211	16.8	44.6	5.6	0.52	2.2	43.0	.0036	.0038	.0010	.034
3212	16.9	44.7	5.2	0.38	2.0	43.4	.0034	.0042	.0009	.049
4211	15.9	44.2	5.6	0.54	2.2	41.9	.0036	.0054	.0009	.040
4212	16.0	44.4	5.2	1.17	2.1	41.7	.0036	.0045	.0008	.054
1311	15.3	45.0	5.3	0.53	2.2	43.8	.0035	.0036	.0009	.049
1312	15.9	44.9	5.8	0.78	2.0	43.0	.0036	.0045	.0009	.051
2311	14.8	44.7	5.6	0.66	2.2	43.0	.0036	.0042	.0008	.052
2312	14.9	44.2	5.7	0.78	2.0	42.3	.0035	.0038	.0008	.050
3311	14.7	44.9	5.6	0.70	2.1	44.5	.0035	.0036	.0009	.049
3312	14.8	45.0	5.5	1.06	2.1	44.5	.0038	.0029	.0009	.051
4311	14.6	45.1	5.8	0.66	2.0	44.3	.0038	.0036	.0007	.053
4312	14.5	45.0	6.0	0.81	2.0	43.1	.0042	.0056	.0009	.053
1121	17.1	45.8	5.7	0.15	2.7	46.9	.0030	.0041	.0008	.092
1122	17.1	46.0	6.1	0.50	2.7	47.4	.0033	.0044	.0009	.093
2121	18.3	46.2	5.8	0.37	2.9	47.0	.0046	.0043	.0010	.072
2122	17.8	46.6	5.8	0.06	3.0	46.3	.0048	.0045	.0010	.110
3121	16.5	46.0	5.7	0.37	2.8	48.0	.0049	.0044	.0010	.091
3122	16.1	46.4	5.8	0.24	2.7	47.9	.0072	.0045	.0010	.088
4121	16.4	47.3	6.1	0.06	2.6	50.5	.0047	.0046	.0010	.110
4122	16.7	47.5	6.1	0.32	2.5	50.3	.0050	.0044	.0011	.091
1131	15.5	48.2	6.4	0.17	2.5	51.5	.0033	.0039	.0009	.095
1132	15.5	47.8	6.3	0.29	2.5	51.3	.0033	.0040	.0010	.075
2131	14.9	48.0	6.3	0.15	2.6	50.8	.0033	.0040	.0012	.071
2132	15.3	47.9	6.3	0.63	2.6	50.3	.0032	.0042	.0009	.073
3131	14.9	49.9	6.8	0.28	2.8	54.3	.0034	.0046	.0011	.096
3132	14.5	49.4	6.5	0.22	2.7	53.8	.0033	.0047	.0009	.077
4131	14.5	47.5	6.7	0.90	2.7	51.0	.0034	.0044	.0012	.185
4132	15.0	48.7	5.5	0.41	2.8	52.2	.0035	.0045	.0009	.076
1221	15.5	45.2	5.8	0.65	2.2	43.8	.0042	.0037	.0009	.044
1222	15.3	44.8	5.8	0.55	2.2	43.7	.0036	.0045	.0008	.058
2221	16.8	44.4	5.8	0.55	2.1	41.4	.0040	.0041	.0009	.036
2222	17.5	43.4	5.5	0.50	2.0	40.6	.0035	.0035	.0009	.051
3221	16.6	44.3	5.8	0.54	1.9	42.0	.0038	.0040	.0010	.050
3222	16.8	44.1	5.5	0.45	1.9	41.9	.0036	.0047	.0008	.055
4221	17.0	45.2	6.0	0.63	2.2	48.2	.0038	.0040	.0009	.057
4222	16.4	44.9	5.8	0.54	2.0	43.4	.0065	.0042	.0009	.060
1231	16.8	47.0	6.0	0.36	2.4	47.4	.0031	.0038	.0026	.075
1232	16.3	46.4	6.2	0.21	2.4	46.8	.0033	.0035	.0009	.073
2231	16.7	46.0	6.1	1.31	2.2	47.4	.0030	.0035	.0010	.072
2232	17.3	46.1	6.1	0.22	2.2	46.0	.0032	.0037	.0009	.072
3231	16.4	45.9	6.1	1.11	2.2	45.7	.0032	.0041	.0011	.072
3232	16.2	45.7	6.1	0.37	2.2	45.3	.0033	.0039	.0009	.072
4231	16.3	45.9	6.1	0.18	2.2	46.4	.0030	.0037	.0010	.072
4232	16.5	45.8	6.3	0.24	2.1	45.9	.0034	.0041	.0009	.072
1321	15.0	45.5	5.7	0.61	2.3	43.5	.0031	.0038	.0007	.050
1322	15.1	45.5	5.9	0.37	2.1	43.1	.0055	.0042	.0009	.059
2321	14.4	45.6	5.5	0.62	2.2	44.7	.0035	.0042	.0008	.057
2322	15.0	45.9	5.5	0.52	2.2	45.1	.0059	.0041	.0009	.059
3321	15.0	45.6	5.7	0.62	2.1	44.9	.0035	.0044	.0006	.053
3322	15.2	45.8	5.7	0.43	2.2	45.0	.0044	.0044	.0009	.055
4321	15.1	45.9	5.5	0.82	2.3	45.3	.0035	.0039	.0007	.054
4322	14.6	45.0	5.5	0.48	2.2	44.9	.0058	.0036	.0008	.058
1331	16.3	44.4	5.4	0.69	2.1	43.9	.0034	.0043	.0009	.061
1332	16.4	44.1	5.5	0.54	2.1	43.5	.0032	.0041	.0009	.061
2331	14.2	45.1	5.5	0.58	1.9	45.2	.0036	.0046	.0006	.058
2332	14.3	45.2	5.5	0.47	2.0	44.7	.0066	.0042	.0008	.062
3331	14.4	43.7	5.5	0.55	2.1	43.2	.0034	.0036	.0009	.060
3332	14.4	44.1	5.4	0.43	1.8	42.4	.0041	.0041	.0009	.070
4331	14.7	43.5	5.8	0.55	2.0	42.1	.0034	.0041	.0008	.051
4332	14.7	43.4	5.1	0.47	2.0	41.7	.0044	.0041	.0009	.060

TABLE B-2. (CONT'D)

CODE abcd	ZN	CU	MG	AL	CA	CR	FE	PB	SI
1111	1.30	.22	1.60	4.10	7.90	.50	13.90	.25	15.50
1112	1.40	.24	1.60	4.00	8.30	.50	14.00	.24	15.00
2111	1.40	.22	1.70	4.10	7.80	.52	11.60	.20	17.00
2112	1.30	.22	1.60	4.00	8.00	.53	13.80	.22	17.00
3111	1.40	.24	1.60	4.30	8.00	.53	13.80	.21	17.30
3112	1.30	.24	1.70	4.10	8.10	.51	12.30	.24	15.50
4111	1.20	.22	1.50	4.10	7.80	.48	15.00	.27	15.00
4112	1.10	.20	1.60	4.00	8.10	.56	16.50	.27	17.30
1211	1.00	.26	2.30	4.00	8.40	.49	11.10	.20	15.80
1212	1.10	.28	2.30	4.00	11.00	.45	13.20	.22	15.00
2211	1.00	.24	2.40	4.10	10.00	.49	11.30	.25	15.60
2212	1.00	.25	2.20	4.00	10.20	.43	13.50	.27	14.10
3211	1.00	.24	2.30	4.10	10.00	.47	11.40	.26	14.20
3212	1.00	.27	2.40	4.00	10.10	.43	13.20	.29	14.20
4211	1.00	.23	2.20	4.10	9.90	.47	11.70	.28	15.20
4212	1.10	.32	2.20	4.10	10.30	.45	13.30	.27	14.30
1311	1.10	.35	2.30	4.30	10.00	.43	11.10	.28	13.90
1312	1.10	.53	2.40	4.10	10.50	.46	13.70	.30	14.10
2311	1.00	.22	2.20	4.10	10.00	.43	11.60	.26	15.40
2312	1.10	.32	2.20	4.20	10.80	.45	13.40	.27	14.30
3311	1.00	.24	2.10	4.20	10.00	.48	11.30	.22	14.40
3312	1.00	.24	2.30	4.10	11.30	.45	13.50	.20	14.10
4311	1.10	.26	2.30	4.20	10.10	.48	13.20	.25	14.20
4312	1.10	.24	2.30	4.10	11.00	.46	13.30	.27	14.30
1121	1.30	.26	1.60	4.00	7.90	.49	15.30	.23	17.00
1122	1.20	.33	1.70	4.30	8.00	.50	15.00	.26	15.00
2121	1.20	.34	1.50	3.80	8.00	.43	11.50	.26	14.60
2122	1.20	.38	1.60	4.00	8.00	.49	11.70	.23	13.20
3121	1.20	.30	1.70	3.80	7.00	.51	11.80	.25	13.20
3122	1.20	.30	1.60	4.00	8.00	.51	11.90	.28	13.00
4121	1.20	.32	1.70	3.80	8.00	.51	12.60	.25	13.20
4122	1.20	.32	1.70	3.80	8.00	.52	12.30	.27	11.80
1131	1.20	.31	1.70	3.70	8.00	.50	12.30	.26	13.20
1132	1.00	.25	1.80	3.90	8.90	.48	13.80	.26	14.10
2131	1.10	.27	1.70	3.90	8.70	.50	11.90	.25	13.40
2132	1.10	.27	1.80	4.10	8.80	.49	13.40	.23	11.90
3131	1.10	.28	1.80	3.80	8.90	.47	12.90	.23	11.80
3132	1.10	.26	1.80	4.10	8.00	.48	13.70	.24	12.90
4131	1.10	.23	1.80	4.00	8.00	.43	14.40	.24	13.80
4132	1.10	.29	1.80	4.00	8.00	.48	13.60	.25	13.00
1221	1.10	.24	2.10	4.20	8.30	.51	13.50	.19	14.60
1222	1.00	.22	2.10	4.20	9.90	.47	13.70	.25	13.50
2221	1.00	.20	2.00	4.10	8.90	.46	11.30	.23	12.70
2222	1.00	.23	2.10	4.20	9.20	.43	13.70	.25	14.10
3221	1.10	.23	2.10	4.00	8.90	.47	11.30	.25	14.60
3222	1.10	.25	2.20	4.10	9.20	.44	13.30	.26	14.20
4221	1.10	.26	2.10	4.10	8.90	.49	11.60	.22	14.60
4222	1.10	.25	2.20	4.20	9.60	.45	14.30	.24	14.20
1231	1.00	.25	1.90	4.00	8.80	.48	13.20	.25	13.50
1232	1.00	.24	1.80	4.00	8.60	.51	12.90	.22	13.20
2231	1.10	.24	1.90	4.10	8.10	.49	13.10	.25	13.10
2232	1.10	.24	1.90	4.10	8.00	.49	12.50	.24	13.70
3231	1.10	.24	1.80	4.30	8.00	.43	12.90	.27	13.50
3232	1.10	.24	1.90	4.10	7.90	.49	12.60	.25	13.20
4231	1.10	.26	1.80	4.20	8.30	.48	12.90	.25	13.50
4232	1.10	.26	1.90	4.10	8.00	.51	12.30	.24	13.20
1321	1.10	.44	2.20	4.20	10.50	.43	11.50	.26	14.40
1322	1.10	.51	2.30	4.20	11.00	.44	13.00	.23	14.00
2321	1.00	.22	2.20	4.20	11.20	.48	11.50	.20	14.10
2322	1.10	.24	2.30	4.00	11.10	.45	13.30	.21	14.20
3321	1.10	.20	2.30	4.20	11.20	.46	11.40	.26	14.90
3322	1.10	.26	2.30	4.00	10.80	.47	13.50	.22	14.70
4321	1.00	.18	2.20	4.00	11.00	.48	11.50	.24	13.80
4322	1.00	.24	2.20	4.20	11.70	.47	13.30	.21	14.30
1331	1.20	.18	2.30	4.10	10.50	.48	11.40	.24	14.30
1332	1.10	.23	2.30	4.10	11.00	.48	13.60	.25	14.60
2331	1.00	.22	2.20	4.30	11.80	.48	12.80	.27	14.80
2332	1.10	.27	2.30	4.20	11.00	.48	13.00	.26	15.00
3331	1.00	.23	2.20	4.20	11.50	.47	11.50	.29	14.30
3332	1.10	.25	2.20	4.10	11.00	.45	13.30	.29	14.90
4331	1.00	.23	2.20	4.20	10.10	.45	11.40	.29	14.20
4332	1.10	.25	2.20	4.00	11.20	.44	13.10	.27	14.90

TABLE B-3. INCINERATOR ASH

CODE - abcd	-	a = temperature level 1 to 4
		b = feed rate level 1 to 3
		c = shaft speed level 1 to 3
		d = sample number 1 to 2

All other elements expressed as a weight percent of the total ash solids

TP	-	total phosphorus
TKN	-	total Kjeldahl nitrogen
TC	-	total carbon

TABLE B-3. INCINERATOR ASH

CODE abcd	TP	TKN	S	TC	AS	CD	HG	NI
1111	6.00	0.13	1.30	.45	.0040	.0027	.0000090	.085
1112	5.80	0.07	1.20	.40	.0045	.0027	.0000080	.090
2111	6.00	0.09	1.10	.31	.0041	.0016	.0000010	.095
2112	5.80	0.11	1.10	.30	.0040	.0042	.0000010	.090
3111	6.20	0.12	.79	.18	.0044	.0010	.0000005	.100
3112	6.20	0.04	.83	.17	.0038	.0011	.0000020	.095
4111	6.50	0.11	.39	.07	.0041	.0009	.0000005	.100
4112	6.50	0.02	.39	.07	.0037	.0009	.0000010	.100
1211	5.80	0.41	1.30	.16	.0033	.0040	.0000016	.048
1212	5.60	0.11	1.20	.19	.0049	.0035	.0000014	.050
2211	5.80	0.37	1.20	.46	.0026	.0025	.0000012	.048
2212	5.80	0.11	1.20	.48	.0035	.0025	.0000011	.050
3211	5.80	0.21	.80	.13	.0028	.0020	.0000022	.050
3212	5.60	0.04	.84	.17	.0038	.0023	.0000026	.050
4211	6.00	0.58	.77	.06	.0041	.0028	.0000011	.050
4212	5.80	0.11	.72	.08	.0035	.0035	.0000007	.048
1311	6.00	0.39	1.30	.74	.0040	.0043	.0000020	.048
1312	5.80	0.11	1.20	.76	.0042	.0040	.0000019	.050
2311	6.00	0.04	1.20	.69	.0034	.0033	.0000011	.053
2312	5.70	0.04	1.20	.66	.0027	.0030	.0000007	.055
3311	6.00	0.00	1.10	.54	.0029	.0028	.0000020	.048
3312	5.90	0.04	1.00	.53	.0031	.0025	.0000010	.055
4311	6.20	0.14	.79	.07	.0038	.0023	.0000015	.053
4312	6.20	0.00	.77	.05	.0035	.0025	.0000009	.055
1121	6.00	0.10	1.50	1.10	.0039	.0020	.0000050	.100
1122	6.00	0.04	1.40	1.10	.0038	.0020	.0000030	.095
2121	6.10	0.05	1.20	.42	.0041	.0018	.0000005	.120
2122	6.20	0.09	1.20	.39	.0028	.0018	.0000015	.110
3121	6.40	0.03	.87	.26	.0030	.0009	.0000005	.120
3122	6.30	0.00	.88	.24	.0030	.0009	.0000005	.120
4121	6.50	0.10	.46	.18	.0028	.0009	.0000018	.110
4122	6.50	0.00	.49	.15	.0029	.0009	.0000005	.100
1131	7.10	0.00	1.10	.24	.0024	.0027	.0000005	.076
1132	7.00	0.25	1.10	.27	.0032	.0027	.0000005	.078
2131	6.90	0.21	.96	.18	.0025	.0029	.0000005	.087
2132	6.90	0.15	1.10	.20	.0023	.0028	.0000005	.079
3131	7.20	0.25	.64	.20	.0026	.0017	.0000005	.085
3132	7.30	0.26	.64	.16	.0042	.0017	.0000005	.088
4131	7.20	0.39	.67	.85	.0023	.0017	.0000062	.085
4132	7.20	0.26	.66	.84	.0026	.0017	.0000061	.096
1221	5.90	0.33	1.10	1.10	.0037	.0025	.0000035	.065
1222	6.00	0.15	1.20	1.10	.0034	.0028	.0000026	.058
2221	5.90	0.03	1.10	.29	.0030	.0040	.0000016	.053
2222	5.90	0.07	1.10	.31	.0034	.0035	.0000014	.050
3221	5.70	0.19	.90	.24	.0026	.0030	.0000025	.058
3222	5.80	0.11	.92	.28	.0037	.0034	.0000015	.050
4221	6.00	0.16	.69	.07	.0033	.0025	.0000012	.050
4222	5.80	0.40	.67	.12	.0039	.0035	.0000011	.048
1231	6.40	0.18	1.20	.34	.0024	.0025	.0000005	.077
1232	6.40	0.60	1.10	.34	.0027	.0025	.0000005	.077
2231	6.50	0.00	.95	.22	.0036	.0015	.0000005	.076
2232	6.30	0.17	.95	.21	.0026	.0014	.0000005	.088
3231	6.50	0.00	.89	.13	.0030	.0007	.0000005	.078
3232	6.30	0.03	.96	.12	.0028	.0006	.0000005	.077
4231	6.80	0.06	.35	.09	.0025	.0009	.0000017	.087
4232	6.80	0.00	.35	.09	.0024	.0008	.0000005	.076
1321	6.00	0.11	1.20	.48	.0035	.0030	.0000016	.058
1322	5.90	0.04	1.20	.46	.0037	.0035	.0000020	.063
2321	6.10	0.04	1.20	.92	.0030	.0025	.0000016	.055
2322	5.90	0.13	1.20	.91	.0034	.0023	.0000020	.055
3321	6.20	0.04	.87	.22	.0030	.0025	.0000011	.055
3322	6.00	0.17	.87	.26	.0033	.0025	.0000015	.053
4321	6.20	0.00	.70	.14	.0034	.0018	.0000010	.060
4322	6.00	0.10	.69	.17	.0033	.0023	.0000010	.053
1331	6.00	0.14	1.20	.50	.0030	.0030	.0000009	.063
1332	5.80	0.15	1.30	.57	.0030	.0035	.0000011	.060
2331	6.10	0.17	1.20	.38	.0030	.0040	.0000014	.058
2332	6.00	0.20	1.20	.42	.0032	.0035	.0000016	.058
3331	6.10	0.23	.96	.22	.0030	.0028	.0000011	.060
3332	5.70	0.00	.99	.25	.0044	.0038	.0000016	.058
4331	6.10	0.36	.80	.12	.0035	.0023	.0000009	.070
4332	6.00	0.08	.79	.18	.0035	.0025	.0000011	.050

TABLE B-3. (CONT'D)

CODE abcd	ZN	CU	MG	AL	CA	CR	FE	PB	SI
1111	1.30	.22	2.00	4.30	9.20	.50	13.50	.25	16.50
1112	1.40	.23	1.90	4.20	8.90	.54	14.40	.26	16.20
2111	1.40	.24	2.00	4.00	9.00	.56	15.30	.23	15.90
2112	1.40	.22	1.90	4.30	8.50	.53	14.10	.21	16.20
3111	1.40	.24	2.00	4.10	9.10	.51	14.70	.21	16.00
3112	1.40	.23	2.00	4.20	9.00	.52	14.40	.20	16.00
4111	1.40	.25	1.90	4.00	9.10	.53	15.60	.21	16.00
4112	1.30	.24	1.80	4.00	8.40	.51	15.60	.19	16.00
1211	1.20	.22	2.20	4.20	10.00	.48	14.10	.21	13.30
1212	1.20	.31	2.20	4.20	10.00	.45	14.00	.23	12.90
2211	1.20	.25	2.10	4.30	10.00	.45	13.80	.19	13.30
2212	1.10	.28	2.10	4.00	10.20	.41	13.20	.21	11.50
3211	1.20	.27	2.30	4.20	11.00	.47	15.00	.28	13.40
3212	1.20	.29	2.20	4.10	10.00	.45	12.90	.24	11.70
4211	1.20	.25	2.10	4.20	11.00	.45	13.70	.30	14.50
4212	1.20	.32	2.30	4.10	10.20	.44	14.20	.31	13.30
1311	1.20	.29	2.10	4.30	10.80	.47	13.60	.30	12.20
1312	1.20	.30	2.20	4.20	10.20	.44	13.00	.30	12.20
2311	1.20	.26	2.30	4.30	10.00	.48	14.40	.28	12.60
2312	1.20	.31	2.30	4.20	9.90	.44	13.90	.31	12.60
3311	1.20	.26	2.20	4.30	10.20	.47	16.40	.27	11.80
3312	1.20	.30	2.30	4.30	10.60	.42	13.20	.29	12.60
4311	1.30	.29	2.40	4.30	11.00	.48	14.20	.29	13.90
4312	1.20	.29	2.30	4.20	10.50	.46	13.40	.32	12.60
1121	1.30	.22	1.80	4.00	8.40	.49	15.60	.22	16.00
1122	1.30	.22	1.80	4.20	8.50	.49	15.60	.22	16.00
2121	1.30	.23	1.90	3.90	8.20	.48	13.00	.22	14.40
2122	1.30	.24	1.90	4.20	8.20	.51	12.50	.24	14.60
3121	1.40	.26	1.90	3.80	8.40	.50	13.30	.23	14.80
3122	1.40	.25	1.90	3.90	8.70	.53	12.80	.23	14.60
4121	1.30	.27	1.90	4.20	8.50	.51	13.30	.21	13.30
4122	1.40	.27	1.90	3.80	8.70	.55	13.40	.21	14.20
1131	1.20	.22	2.00	3.70	9.50	.51	12.90	.25	11.40
1132	1.20	.26	2.00	3.80	8.80	.48	14.80	.22	13.40
2131	1.30	.24	2.00	4.00	9.10	.53	13.30	.25	13.00
2132	1.20	.26	2.00	4.00	9.00	.49	12.80	.26	12.50
3131	1.30	.28	2.00	3.80	9.00	.52	13.40	.24	13.40
3132	1.30	.24	2.10	4.10	10.00	.51	14.30	.24	13.50
4131	1.30	.27	2.00	4.00	9.40	.48	13.90	.22	13.00
4132	1.30	.27	2.00	4.00	8.90	.44	14.10	.24	12.90
1221	1.20	.28	2.20	4.30	9.30	.50	14.60	.28	12.90
1222	1.20	.27	2.10	4.20	9.20	.45	14.10	.24	11.80
2221	1.10	.27	2.10	4.30	10.00	.46	13.60	.28	12.90
2222	1.20	.28	2.10	4.30	9.00	.45	13.70	.25	12.40
3221	1.20	.31	2.20	4.10	9.90	.50	14.40	.30	13.30
3222	1.20	.27	2.10	4.30	9.00	.43	14.00	.27	12.60
4221	1.20	.32	2.20	4.30	9.40	.50	14.20	.28	13.70
4222	1.10	.23	2.00	4.20	9.50	.41	13.60	.28	12.20
1231	1.20	.24	2.00	4.10	9.00	.42	13.60	.26	13.00
1232	1.20	.25	2.00	4.00	9.20	.44	13.90	.23	13.30
2231	1.20	.23	2.00	4.10	10.00	.45	13.10	.25	13.10
2232	1.20	.25	2.00	4.30	9.40	.45	13.70	.25	13.80
3231	1.20	.25	2.00	4.30	9.20	.43	13.20	.22	13.20
3232	1.20	.22	2.10	4.10	9.50	.44	13.50	.19	13.10
4231	1.20	.27	2.10	4.20	9.00	.47	14.30	.20	13.40
4232	1.20	.26	2.10	4.10	8.90	.47	14.30	.20	12.90
1321	1.30	.31	2.20	4.20	10.40	.47	13.10	.29	12.60
1322	1.20	.32	2.20	4.20	10.50	.45	11.90	.28	13.40
2321	1.20	.28	2.20	4.30	10.60	.45	13.10	.26	11.70
2322	1.20	.32	2.20	4.10	10.80	.46	13.20	.26	11.90
3321	1.20	.30	2.30	4.20	11.00	.46	12.20	.27	12.60
3322	1.20	.33	2.20	4.20	11.00	.45	13.40	.28	12.40
4321	1.30	.33	2.40	4.20	11.00	.48	14.20	.28	12.90
4322	1.20	.31	2.30	4.20	11.00	.45	12.20	.28	12.60
1331	1.30	.24	2.20	4.30	10.80	.52	14.10	.32	12.60
1332	1.30	.30	2.20	4.20	11.00	.52	13.00	.29	11.80
2331	1.30	.33	2.40	4.30	10.50	.47	13.20	.28	12.50
2332	1.30	.34	2.20	4.20	10.90	.48	13.40	.32	11.30
3331	1.30	.27	2.30	4.20	10.40	.48	13.80	.28	12.60
3332	1.20	.32	2.20	4.30	10.20	.49	13.50	.30	12.20
4331	1.20	.31	2.30	4.20	10.50	.48	13.50	.27	12.60
4332	1.20	.30	2.20	4.00	10.20	.49	13.20	.29	11.70

TABLE B-4. SCRUBBER WATER

CODE - abcd	-	a = temperature level 1 to 4
		b = feed rate level 1 to 3
		c = shaft speed level 1 to 3
		d = sample number 1 to 2

All elements expressed as mg/L

TP	-	total phosphorus
TKN	-	total Kjeldahl nitrogen
TC	-	total carbon

TABLE B-4. SCRUBBER WATER

CODE abcd	TP	TKN	S	TC	AS	CD	HG	NI
1111	1.100	21.	60.	22.	.005	.023	0.000	.070
1112	.900	20.	60.	23.	.005	.021	0.000	.060
2111	1.100	22.	60.	28.	.005	.038	0.000	.060
2112	1.300	20.	60.	31.	.005	.036	0.000	.060
3111	1.400	23.	70.	24.	.005	.041	0.000	.050
3112	1.700	20.	70.	34.	.005	.045	0.000	.060
4111	2.700	18.	60.	28.	.005	.035	0.000	.110
4112	2.600	15.	70.	29.	.005	.040	0.000	.130
1211	.005	30.	40.	38.	.006	.005	0.000	.050
1212	.005	26.	40.	38.	.007	.012	0.000	.040
2211	.005	32.	30.	50.	.008	.020	0.000	.020
2212	.100	29.	30.	51.	.006	.021	0.000	.010
3211	.005	26.	60.	20.	.009	.042	0.000	.060
3212	.400	22.	60.	20.	.008	.035	0.000	.030
4211	.005	30.	60.	28.	.010	.030	0.000	.050
4212	.100	26.	60.	27.	.012	.026	0.000	.060
1311	.005	29.	50.	46.	.010	.008	0.000	.060
1312	.400	30.	40.	57.	.011	.011	0.000	.090
2311	.005	25.	30.	35.	.006	.020	0.000	.040
2312	.100	23.	40.	34.	.009	.021	0.000	.030
3311	.005	27.	50.	44.	.008	.017	0.000	.040
3312	.005	24.	50.	35.	.007	.020	0.000	.030
4311	.005	31.	50.	53.	.007	.010	0.000	.040
4312	.005	33.	50.	55.	.007	.008	0.000	.030
1121	.005	24.	50.	41.	.005	.026	0.000	.030
1122	.005	24.	50.	43.	.005	.024	0.000	.030
2121	.100	19.	120.	19.	.016	.025	0.000	.020
2122	.200	19.	120.	16.	.011	.027	0.000	.040
3121	.100	20.	120.	17.	.008	.027	0.000	.020
3122	.005	23.	130.	20.	.007	.026	0.000	.020
4121	.300	31.	140.	39.	.020	.031	0.000	.020
4122	.300	33.	140.	41.	.017	.033	0.000	.020
1131	.200	26.	100.	31.	.009	.013	0.000	.060
1132	.400	25.	90.	34.	.090	.015	0.000	.060
2131	.300	31.	110.	44.	.008	.006	0.000	.040
2132	.200	31.	110.	46.	.007	.008	0.000	.040
3131	.300	23.	110.	25.	.006	.018	0.000	.030
3132	.100	25.	120.	22.	1.070	.021	0.000	.030
4131	2.800	19.	140.	15.	.015	.032	0.000	.050
4132	2.500	20.	140.	14.	.016	.031	0.000	.050
1221	.005	35.	40.	43.	.006	.015	0.000	.010
1222	.005	32.	40.	43.	.008	.020	0.000	.020
2221	.005	20.	30.	43.	.008	.010	0.000	.050
2222	.005	19.	20.	35.	.012	.010	0.000	.080
3221	.005	26.	50.	35.	.009	.018	0.000	.080
3222	.005	23.	50.	47.	.010	.012	0.000	.060
4221	.005	24.	50.	26.	.006	.026	0.000	.040
4222	.005	23.	50.	25.	.007	.023	0.000	.020
1231	.300	34.	110.	50.	.010	.015	0.000	.100
1232	.500	32.	110.	45.	.009	.014	0.000	.080
2231	.100	28.	90.	40.	.004	.017	0.000	.020
2232	.200	26.	90.	39.	.098	.021	0.000	.030
3231	.005	27.	100.	26.	.007	.020	0.000	.020
3232	.100	25.	110.	25.	.010	.022	0.000	.020
4231	.100	32.	130.	33.	.013	.027	0.000	.030
4232	.800	26.	140.	26.	.014	.029	0.000	.030
1321	.005	26.	40.	43.	.010	.015	0.000	.090
1322	.005	26.	40.	47.	.009	.013	0.000	.080
2321	.005	36.	50.	39.	.010	.026	0.000	.030
2322	.005	38.	50.	39.	.008	.025	0.000	.030
3321	.005	23.	50.	33.	.014	.018	0.000	.100
3322	.100	21.	50.	32.	.008	.013	0.000	.060
4321	.005	22.	60.	21.	.008	.030	0.000	.040
4322	.400	21.	60.	22.	.006	.028	0.000	.040
1331	.005	21.	40.	37.	.012	.019	0.000	.160
1332	.100	28.	40.	36.	.005	.012	0.000	.110
2331	.005	25.	50.	43.	.012	.011	0.000	.090
2332	.100	40.	50.	48.	.006	.009	0.000	.090
3331	.005	24.	40.	59.	.013	.011	0.000	.090
3332	.400	31.	40.	54.	.005	.011	0.000	.090
4331	.005	13.	20.	40.	.011	.010	0.000	.070
4332	.100	18.	20.	41.	.006	.005	0.000	.050

TABLE B-4. (CONT'D)

CODE abcd	ZN	CU	MG	AL	CA	CR	FE	PB	SI
1111	.640	.117	6.50	1.25	46.	.20	4.80	.27	1.50
1112	.560	.098	6.20	1.15	42.	.19	4.40	.30	1.00
2111	.540	.089	6.20	1.00	42.	.18	3.80	.55	1.83
2112	.700	.110	6.40	1.15	42.	.20	5.40	.61	1.90
3111	.660	.077	6.20	1.00	42.	.14	3.40	.97	1.90
3112	.830	.089	6.50	1.05	43.	.19	5.00	1.05	2.50
4111	1.170	.230	7.50	2.40	49.	.40	10.80	.76	3.40
4112	1.190	.220	7.20	2.30	46.	.40	11.00	.93	3.40
1211	.780	.170	7.30	1.60	43.	.29	7.00	.30	3.00
1212	.820	.190	7.70	1.80	45.	.30	7.40	.39	3.60
2211	.250	.054	6.50	.57	40.	.08	2.00	.23	1.50
2212	.280	.055	6.80	.67	42.	.08	2.20	.27	1.40
3211	1.100	.230	8.30	1.90	48.	.37	8.60	.71	3.60
3212	.750	.155	8.00	1.60	45.	.20	4.80	.52	2.90
4211	.920	.200	8.20	1.60	47.	.30	7.20	.58	3.40
4212	.930	.240	9.00	1.90	50.	.32	7.40	.62	3.80
1311	.900	.260	8.50	1.70	50.	.30	7.60	.35	3.60
1312	1.100	.385	8.70	2.20	53.	.42	10.00	.42	3.70
2311	.520	.110	6.90	.98	40.	.16	4.40	.37	2.20
2312	.520	.105	7.30	1.10	45.	.17	4.60	.34	2.00
3311	.650	.210	7.70	.92	45.	.17	4.40	.48	2.20
3312	.450	.110	9.90	1.80	46.	.13	4.20	.40	4.60
4311	.650	.200	8.50	1.00	50.	.18	4.60	.31	2.70
4312	.500	.145	7.30	.85	45.	.14	3.60	.30	2.20
1121	.310	.057	6.40	.55	44.	.11	2.80	.27	1.70
1122	.270	.053	6.30	.52	42.	.10	2.50	.22	1.60
2121	.350	.044	7.40	.55	44.	.08	1.52	.37	1.20
2122	.410	.055	7.70	.68	36.	.08	1.70	.36	1.30
3121	.310	.036	6.50	.46	36.	.07	1.50	.35	1.20
3122	.280	.036	7.10	.50	37.	.08	1.67	.33	1.30
4121	.630	.047	6.60	.62	37.	.05	1.34	.75	1.70
4122	.570	.039	6.70	.50	39.	.05	1.08	.78	1.60
1131	.680	.142	7.40	1.25	40.	.28	6.40	.22	2.90
1132	.870	.191	8.20	1.64	43.	.35	8.00	.28	3.30
2131	.470	.114	7.40	.96	42.	.18	4.30	.14	2.40
2132	.500	.107	7.20	.90	41.	.21	4.32	.15	2.50
3131	.310	.058	6.80	.55	38.	.09	2.15	.22	2.00
3132	.430	.089	7.80	.65	39.	.15	2.90	.28	1.90
4131	.950	.146	7.80	1.76	42.	.28	5.46	.65	3.30
4132	.880	.145	7.60	1.60	37.	.19	5.22	.67	2.80
1221	.240	.078	6.50	.45	36.	.07	1.70	.20	1.20
1222	.460	.090	6.70	.77	40.	.14	3.40	.26	1.70
2221	.850	.240	8.50	1.70	50.	.33	7.70	.32	3.00
2222	1.140	.325	8.80	2.10	50.	.45	11.60	.38	3.70
3221	1.360	.315	8.50	2.70	52.	.46	12.60	.61	4.40
3222	1.080	.280	8.80	2.00	50.	.38	10.20	.47	4.50
4221	.900	.170	7.50	1.50	45.	.28	6.60	.56	3.00
4222	.660	.135	7.40	1.10	42.	.20	4.80	.46	2.70
1231	1.210	.333	8.70	2.30	48.	.47	10.85	.43	4.50
1232	1.000	.227	7.80	2.05	46.	.40	9.15	.38	4.70
2231	.290	.058	7.30	.69	36.	.10	2.40	.18	1.70
2232	.320	.062	7.50	.72	38.	.11	2.48	.19	1.90
3231	.230	.042	6.90	.44	38.	.14	1.56	.34	1.00
3232	.200	.034	7.50	.43	36.	.05	1.30	.35	1.00
4231	.530	.069	7.40	.60	46.	.09	1.93	.52	1.80
4232	.480	.060	6.80	.78	36.	.09	2.04	.61	1.70
1321	1.300	.290	8.70	2.20	50.	.45	10.60	.45	3.80
1322	1.100	.255	8.40	2.20	48.	.38	9.60	.44	4.00
2321	.450	.093	6.80	.75	40.	.14	3.40	.30	1.80
2322	.460	.110	6.90	.95	40.	.15	3.80	.32	1.70
3321	1.360	.355	9.80	2.50	55.	.49	12.20	.53	4.80
3322	1.100	.270	8.70	2.20	52.	.39	11.00	.49	4.00
4321	.970	.155	7.70	1.20	45.	.15	3.40	.48	2.00
4322	.920	.170	7.80	1.60	45.	.21	4.60	.53	2.80
1331	2.400	.518	9.90	3.90	62.	.85	23.20	.72	5.70
1332	1.700	.350	9.00	3.40	55.	.60	15.00	.60	4.50
2331	1.370	.325	9.70	2.50	55.	.46	11.20	.45	4.50
2332	1.220	.300	8.50	2.20	50.	.41	10.20	.42	4.20
3331	1.500	.320	9.40	2.20	60.	.43	11.40	.45	4.30
3332	1.460	.330	9.20	2.50	55.	.48	12.00	.50	4.00
4331	1.200	.248	9.00	2.00	50.	.50	11.20	.42	3.70
4332	1.060	.240	8.40	2.10	50.	.43	10.40	.38	3.00